Evaporation – a tool for sustainable drainage management

Peter Worrall[1], Steve Markham[2], Quintin Murfin[3]

[1]Technical Director, BEd (Hons), MSc, MCIWEM, MIWA, CSci, CEnv, Penny Anderson Associates Limited (Consultant Ecologists), 60 Park Road, Buxton, Derbyshire, SK17 6SN, United Kingdom. +44 1298 27086, e-mail: peter.worrall@pennyanderson.com
[2]Director, Marquis and Lord Limited, 13 John Street, Stratford-upon-Avon, Warwickshire, United Kingdom. +44 1684 565222, email: steve.markham@marquisandlord.com
[3]Chartered Civil Engineer, BEng, MSc, MICE, CEnv, MCIWEM, MCMI, Rosewood, La Longue Rue, St Martin, Jersey, JE3 6ED, United Kingdom. +44 1534 851021, email: q.murfin@hotmail.com

Abstract

Where the use of orthodox controlled hydraulic discharge to watercourse is not possible for the management of urban runoff, alternative strategies need to be considered. At Jersey Airport (Great Britain) the development of a new Fire Training Ground facility was constrained by a prohibition on the disposal of surface runoff to watercourse or ground water (because of low levels of persistent pollutants in the runoff) so a system using evaporation and water re-use was developed to create a unique surface water drainage system without a surface water outfall.

Surface runoff from the training ground catchment, excluding that generated during practice, is contained and stored beneath the permeable paved surface in a storage cell and managed either through evaporation or through harvesting for use in fire fighting practice.

Evaporation is achieved using a patented system of 20 water jets placed around the fire training ground that apply water from the cell to the paved surface. They are automatically switched on when the on-site weather station indicates that there is sufficient evaporative potential. Wind speed and direction are measured to enable the sprays to cover the paved areas within the site boundary.

Further research has been undertaken that has demonstrated that significant evaporation is achievable in patented designs of underground storage cells.

This paper describes the development and modelling of the use of evaporation as a runoff management tool with particular emphasis on spray-on-pavement systems and enhanced passive evaporation from underground storage cells.

The use of spray on pavement systems has been proven as viable and the use of in-cell evaporation is under development.

The Development Sustainable Drainage Systems Technology in the UK

In the United Kingdom, it is normal to find surface waters draining from paved urban surfaces via channels, gullies and pipes to the nearest available water course. This traditional approach is now recognised as exacerbating flood risk because the increase in the rate of runoff conveyance as compared to a 'greenfield' situation. Such rapid runoff from paved surfaces can also result in significant impacts on receiving waters as a result of rapid wash-off of pollutants, particularly during intense storms following periods of dry weather.

Sustainable Drainage Systems (SuDS) have been developed over recent years with the aim of reducing the impact on watercourses by creating systems for developed sites that have runoff profiles that are more comparable to the 'greenfield' situation. The emphasis is on trying to control the runoff nearer to its source, rather than dealing with it as a downstream flooding issue. The techniques include storage and attenuation on site in basins or ponds, the use of swales (vegetated channels) to slow the rate of flow off site and infiltration to ground (soakaways) where soils of adequate permeability are available (and pollution risks are low). Water quality can also be improved by the use of swales and wetland systems that allow the removal of some contaminants (CIRIA 2004).

Permeable paving systems have also been developed, which allow rainwater falling onto the surface to drain between paving units, rather than run off. Porous asphalts that allow water to pass through a surfacing layer perform a similar role. These systems are often seen as advantageous over alternatives such as wetlands because the permeable surfaces can have a more commercial benefit by providing parking etc. In such systems, once water has passed through the paving it can be infiltrated to ground where the soils below have adequate permeability. However, infiltration to ground is not suitable where groundwater pollution protection rules apply or high water table prevents infiltration. Also, contaminated land may be unsuitable for infiltration because of the risk of mobilisation of pollutants. In these cases, a liner below the 'geo-cells' or voided stone can be used to create a storage cell, that allows a storm event to be held, and discharged via a throttled outlet to reduce the peak discharge from the site to rate similar to the 'greenfield' rate.

Jersey Airport Fire Training Ground Redevelopment

The Island of Jersey is located in the English Channel, between the United Kingdom and France, in Europe. Whilst the Island is only 45 square miles in area it has a population of 87,000 people and it has a thriving financial centre as well as a being a tourism destination. The Island has its own Government but follows United Kingdom standards.

Up to 1994, Jersey Airport Fire Training Ground (FTG) was used for fire fighting training with water and foam on simulated aircraft on an unpaved and unsealed surface. As a consequence, hydrocarbons and foams contaminated the ground below. The fire fighting foam used was AFFF, like all foams it has high BOD, however

AFFF also contains Perfluorooctane sulfonate (PFOS)[1] a persistent substance that bioaccumulates. PFOS is now found in the environment from the Artic to the Antarctic. National governments, including the UK (Defra 2005), now restrict or are in the process of regulating its use.

As a consequence of the contamination, adjoining drinking water wells became visibly contaminated with foam, leading to suspension of fire training with foam and the need to provide mains water supplies to affected properties as well as pollution attenuation for the aquatic environment. With the introduction of the Water Resources (Jersey) Law 2000 there was a requirement to remediate the site and a condition placed on the remediation that any replacement fire training facility would not contribute to further pollution of the site.

Objectives and Constraints

The development of the new facility was constrained by a prohibition on the disposal of surface runoff to watercourse or to groundwater because of the water use for public water supply and aquifer flow into a protected area of ecological value.

There were two distinct elements of drainage that would require disposal. Firstly the effluent created by training on the mock aircraft training rig would consist of fire training water and foam, fire fuel and rig cooling water. All these flows mix together in a training exercise and the effluent from the rig would be contaminated with hydrocarbons and foam. Secondly, the vehicle manoeuvring area around the rig would be contaminated with fire fighting foams and other potential pollutants not contained within the fire practice zone. These pollutants would contaminate rainfall runoff. In a normal year fire training would generate 4600 m^3 of effluent with a BOD load of 5000kg. Average rainfall would generate 4100m^3 of mildly contaminated runoff.

Options Evaluation

The disposal of fire training effluent to foul sewer (and hence to the Island's sewage treatment works and then directly to a sea outfall) was acceptable to the sewerage authority, subject to a flow limitation of 0.5l/s. This was achievable with hydraulic attenuation of the runoff generated during fire fighting practice, followed by controlled low rate discharge to sewer in order to meet the Biochemical Oxygen Demand (BOD) loading requirements of the sewage works.

To meet the discharge consent the fire training effluent needs to be attenuated. In practice all the training sessions' effluent is collected before discharge. Shock loads of foam, up to a BOD concentration of 475,600 mg/l, are diluted with other training water such as that used for the drench and wash down. A typical training session could produce an effluent of 27m^3 with a BOD load of 56kg. The 56 kg of BOD

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[1] The major producer of PFOS, 3M, ceased production in 2000.

load has a population equivalent of 900 people and to meet the discharge consent of 4 kg/hour this would have to be discharged over a period of 15 hours.

The most challenging element was the disposal of surface water from the 4660m^2 of paved training area because of the large volume of surface water mildly contaminated with pollutants. Conventional options considered were the disposal of water to the adjacent watercourse or disposal to sea via a dedicated culvert and outfall. Disposal to watercourse was not permitted because the non-degradable foam products in the effluent would be persistent in the environment. Disposal to a long sea outfall by culvert was not economically viable because the site was 2km from the sea.

The only acceptable option that was identified to meet the objectives was the use of an inventive concept of storing the rainfall runoff under the paved area in a lined geo-cellular storage cell (see Figure 1), and then disposing of it by spraying the water onto the paved surface and utilising climatic evaporation (this concept has now been patented UK Patent No 240681, International Patents Pending) combined with the reuse of some of the water for fire training.

Figure 1. Constructing the geo-cellular runoff storage cell.

Development work

The viability of the use of spray evaporative disposal was validated by developing a computer model that simulated the potential evaporation and storage required to meet the seasonal imbalance between rainfall inputs and disposal outputs.

Evaporation from open water has been extensively studied and modelled to develop equations that allow the prediction of evaporation under defined conditions of temperature, humidity, wind and sunshine. In particular, the Penman-Monteith Equation is developed and utilised for this purpose (FAO 1998).

The relationship between evaporation from a wetted pavement surface and open water evaporation had not been researched. A small trial established that evaporation from a wetted surface was sufficient to be considered for useful surface water disposal.

A computer model was developed to simulate potential evaporation with average and extreme annual weather conditions at the site and the storage required when taking into account abstractions from the cell for water reuse. This established the viability of water management utilising the evaporative disposal and water reuse.

The system would contain any contaminants to ensure they are not released to the adjoining environment. The stored water is then applied to the permeable surface using sprays that generate water droplets as opposed to sprays that would generate a fine mist. This is to reduce the risk of drift beyond the boundaries of the site. At the end of the system's life, the residual distillate in the base of the cell would require disposal.

Weather on Jersey is greatly influenced by the fact it is an island situated close to the large land mass of Europe. Frosts are infrequent and despite it proximity to the sea it does not have a strong maritime climate. This is reflected in its moderate annual rainfall (840 mm) and high number of warm dry sunshine days. Also the Airport sits facing the Atlantic Ocean, so there nearly always is a wind. All this helps to create an annual potential evaporation of 1280 mm. As can be seen in Figure 2 below, the annual evaporation is greater than the yearly rainfall, however, winter rainfall exceeds evaporation and there are occasional summer storms and for the fire training ground to function rainfall runoff needs to be stored.

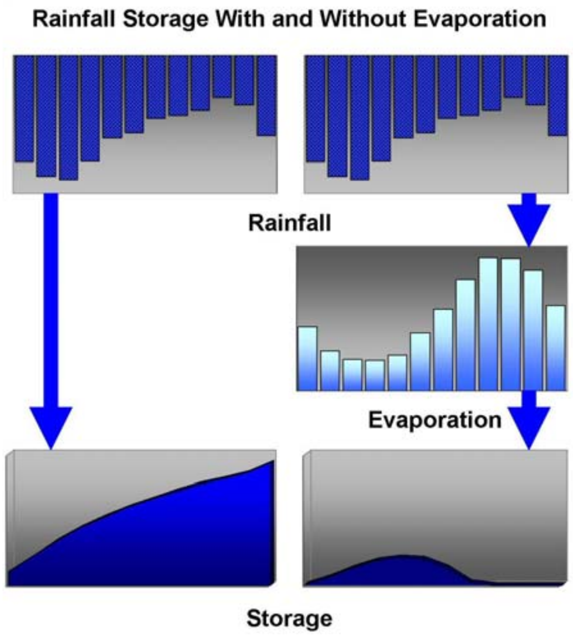

Figure 2. Water Balance in FTG Storage Cell

To assist in calculating the volume of storage required the highest recorded annual rainfall was used; for 2000/2001 (1430 mm) from a record of 50 years. The mathematical model was used to simulate the day to day rainfall runoff and evaporation and calculate the storage required. The model also used the highest recorded monthly and three monthly rainfall together with a contingency for climate change; for climate change all rainfall was increased by 10%. A storage volume of 2200m^3 was recommended after allowance for harvesting for other uses described below.

Implementation of the System

Having established system viability, an implementation scheme was designed and constructed and is now functioning successfully.

During a fire fighting practice all the foam, hydrocarbons and water, used either to fight the training fire or as drench water to keep the training rig cool, drains off impermeable pavers to an 80m^3 attenuation pond. From here the effluent is passed through oil interceptors before being slowly discharged to a sewage treatment works.

Once the fire crews have washed down and left the site, all rainfall and runoff is automatically diverted to an underground storage cell. There are then four destinations for the water:

- the bulk of water is disposed of through managed evaporation;
- some of the water is used to act as a drench for the rig to keep it cool during practice;
- some of the water is used as a wash down after practice; and
- the water can also be used to top up the fire fighting tenders

Evaporation is achieved using a system of 20 water jets placed around the fire training ground (see Figure 3) that apply water from the cell to the paved surface. They are automatically switched on once a fire practice is completed and the vehicles have left the site, and when the on-site weather station indicates that there is sufficient evaporative potential. Wind speed and direction are constantly measured to enable the sprays to only operate within the site boundary

Figure 3. One of the 20 'controlled, evaporation sprays

The system of water management is unique in that it contains and manages all runoff within the site, and except for a limited discharge to foul for the particularly polluted fire practice runoff, the site has no discharge to local watercourse or groundwater.

A SCADA (***S****upervisory* ***C****ontrol* ***A****nd* ***D****ata* ***A****cquisition)* system was developed for the FTG which programmes the water management of the site to operate in a predetermined way, in response to information received through monitoring. The FTG can run unmanned and change its mode of operation. For example, when the fire crews enter the site through a key coded gate, the evaporation system is switched off and drainage is directed to the attenuation pond. On leaving the site, the on-site weather station linked to the control system constantly calculates the Potential Evaporation, delivering a set amount of water for each threshold of evaporation. Wind speed and direction is also constantly monitored, the control system operating the sprinklers that spray only within the site boundary. Flexibility built into the control system allows the evaporation performance to be changed through analysis of the stored monitoring information. The FGT's unique approach to water management meant that the process of on-surface evaporation was untried when construction was complete. However, the control system enabled optimisation of water management performance during a commissioning period when the fabric of the Fire Training Ground was in place.

Further Development

Greenfield runoff rates can equate to as little as 10% of rainfall rates because most of the rainfall is intercepted by plants and evaporated, taken up from the soil by plants as they transpire ('breathe') or is transferred to groundwater. In contrast, urban developments can generate as much as 90% of rainfall as runoff because very little is evaporated to the atmosphere or transferred to groundwater prior to reaching receiving waters.

Some sites where recharge to groundwater is not possible (e.g. contaminated sites or those with high water tables) pose problems for disposal where a convenient watercourse outfall is not available or the runoff is not suitable for discharge to a watercourse.

Permeable pavements with tanked cells can be used to solve the problem of collection of the surface water runoff, but disposal of the rainwater, which may be contaminated, is still a problem.

The studies carried out for the Jersey Airport Fire Training Ground Redevelopment stimulated the authors to investigate the potential for evaporation as a runoff disposal method from paved areas. Analysis of the relationship between the potential evaporation in the UK and rainfall, indicates that the south-east of the country has generally higher potential evaporation than rainfall. This provides the opportunity for the use of evaporation to dispose of excess rainfall on sites with onerous volume or quality discharge constraints.

Evaporation is the transfer of water from the liquid to the gaseous state; it is driven by the difference between vapour pressure at a surface and the air immediately next to it. Evaporation is at its strongest when driven by solar radiation which provides enough energy to overcome the forces between the water molecules.

Three components are needed for evaporation to occur:

1) a source of energy to overcome the latent heat of vaporisation (this can be from solar radiation or the lack of vapour pressure equilibrium between a wet surface and dry air);

2) a mechanism for removing the dry air before it has become saturated as a result of the evaporation (i.e. the wind or ventilation); and
3) a supply of moisture – in calculating Potential Evaporation it is assumed the water is always available.

The “drying power” of air, as determined by the saturation vapour pressure deficit is the difference between the saturated vapour pressure (at temperature T_1) and the actual vapour pressure (at temperature T_1). The gradient of the saturation deficit is a measure of the lack of equilibrium between a wet surface and the air passing over it. The greater the difference the greater the drying power, as the air carries more moisture its drying power is reduced. A supply of fresh air aids the performance of the system.

The ‘spray on pavement’ surface water disposal system is very effective for the particular application at Jersey Airport but would be unsuitable for developments such as car parks where there are continuous activities on site. The Jersey Airport system did not however take account of the potential for passive evaporation within an underground storage cell. Passive evaporation aims to use the available processes of ventilation (including natural wind energy usage) to provide evaporation without an artificial energy supply.

Testing has shown that evaporation from within a cell is normally very limited, because of two factors. Firstly the cells are not usually built with through ventilation and, secondly, the evaporation from water in the base of the cell is limited by the exposed surface area.

A theory was developed that in-cell evaporation efficiency could be enhanced by increasing the evaporative surface area in contact with the airflow and the water loss efficiency of the surfaces, compared to the flow of air over the upper surface of the water stored in the base of the cell.

Two methods of increasing the evaporative surface area per unit area were hypothesised and proven. Wicking consists of the hanging of water absorbing materials into the water. These wicks draw water up, (the draw height depending on the pores or the fabric or other material used) and the increased surface area in contact with air flow increases the absorption of water by the air flow. This concept is complex to construct and has a significant air resistance, and is only advantageous in particular situations. The ‘Lamina’ method is the use of one or more horizontal layers of water absorbing mats below a paved surface to detain water that has percolated through the pavement. If the lamina mat has its surface exposed to the air, e.g. by placing it within a ventilated geo-cell, it will increase the efficiency of evaporative water loss. The lamina mat will dry out by evaporation and is then recharged by subsequent rainfall and throughflow from the permeable surface above. The efficiency of these laminas mats is thought to be high because the evaporation from the underside of the saturated surface is aided by the water surface being fed from above, and hence more likely to provide a wetted surface for evaporation.

Two years of research and trials have been carried out for a UK company called the Sustainable Drainage Partnership Limited (www.sdpartnership.com). The trials have established that the annual trend for in-cell evaporation, whilst higher in summer is strong in the spring and autumn and still significant in winter.

Having established the trends of the evaporative systems, a model of a potential lamina system, and a control without lamina (for comparison) have been constructed. These models represent a full-scale element of a car park system. Natural wind flow is enhanced by a wind driven revolving cowl.

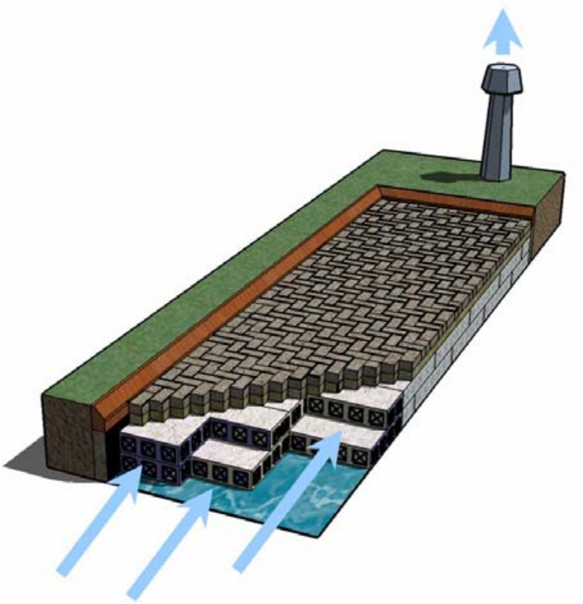

Figure 4. Model of 'Lamina' System

The performance of these trials has been monitored during 2005 and the results show that the Lamina System performance exceeds the system without lamina by a factor of three for the period of the trial to date and the trials are showing that around 40% of the rainfall incident on the surface of the system has evaporated. This is loss comparable to some vegetated sites.

Evaporation in a cell is increased by ventilating the cell, by providing an air flow pathway over the cell base, linked to air intakes and flue outlets. This increases the take up of water by the air through put which is usually unsaturated.

In-cell evaporative enhancement systems have the potential to reduce disposal volume problems on sites with significant constraints for off-site discharge particularly where infiltration to ground is not appropriate.

Conclusion

The use of evaporative disposal as a surface water management tool is feasible, and the potential for application of this method to paved areas with particular discharge or water quality constraints is significant.

The use of evaporative disposal, possibly in combination with water harvesting and re-use generates the potential for urban development characterised by either zero or limited runoff discharge from the site.

The use of spray on pavement systems has been proven as viable and the use of in-cell evaporation is under development.

The future potential of these systems is under further development and their potential role in reducing urban heat islands is being considered.

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