HYDROLOGY AND THE WATER FRAMEWORK DIRECTIVE IN IRELAND

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ABSTRACT

The Water Framework Directive (WFD) has been the catalyst for a considerable amount of data collection, analysis and research, covering a wide range of physical and biological characteristics and involving a wide range of scientific, social and management-related disciplines. This paper starts with a short description of the discipline of hydrology and then identifies the main hydrological aspects of work for the WFD, noting their ecological significance. It also provides some idea of the range of organisations and disciplines involved in the work and of the links between them. Of particular significance is the degree of cooperation between river basin districts in setting up working groups for special studies, helping to avoid overlaps in research.

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INTRODUCTION

The purpose of this paper is to identify and briefly discuss hydrological work and improvements in hydrological knowledge associated with Directive 2000/60/EC (European Parliament and Council 2000), commonly known as the Water Framework Directive (WFD). Of necessity, this paper has to be a personal view, and the author acknowledges his own background in surface water hydrology.

Hydrology is the study of the occurrence, circulation and distribution of water on the earth (Shaw 1994). It includes the consequences of the movement of water and all that the water carries with it. Usually, hydrologists study freshwaters, but occasionally they venture into estuaries and near-shore marine environments, particularly when following the fate and consequences of riverine discharges and their sediment and contaminants. The study of the deeper oceans and seas is left to the oceanographer. Thus, the spatial and physical domain of the hydrologist coincides very closely with that of the WFD, and water plays a key, cross-cutting role in its implementation. Hydrology can be taught from a scientific perspective—for instance, in a geography or geology setting where the major thrust is in understanding the main processes in the hydrological cycle and their links—or from an engineering perspective, where the implications for the management of water, its benefits and risks are studied (Nash *et al.* 1990). The latter approach typically involves a considerable element of data analysis and numerical modelling. This is supported by Lee's (1990) discussion of Nash *et al.* (1990) in which he moves from Dooge's (1986) view that 'the business of hydrology is to solve the water balance equation' to his own suggested definition of hydrology as the 'science that seeks to explain and quantify the water-balance dynamics for any defined spatial scale (from a point to global) and temporal scale (from seconds to years) and their relationships with the physical and chemical transport of matter through the hydrological cycle and with ecology'. This definition, enunciated over a decade before the WFD, very succinctly describes the hydrologist's role in supporting the WFD.

The hydrological cycle (Fig. 1) shows the major stores of water and the principal fluxes between them, and this is the basic conceptualisation on which hydrology is based. Water is evaporated into the atmosphere from the oceans, rivers, lakes, land surface and vegetation. It may be carried some distance by winds before falling as precipitation either on the ocean or on land. Some of the precipitation may be intercepted by vegetation and evaporated back into the atmosphere without reaching the ground surface. The precipitation reaching the ground surface may infiltrate into the ground, run off over the surface or evaporate back into the atmosphere. The water that infiltrates into the soil may percolate downwards to recharge an aquifer or may move laterally to emerge, at a lower location, as a spring or seep. The lateral component of water movement in material above the water table (the vadose zone) is often called 'interflow'. Water that does reach the water table recharges the aquifer and moves through it to emerge at a river or lake bed or at the ocean bottom. The roots of plants may bring water from the soil or aquifer to the surface to be evaporated from

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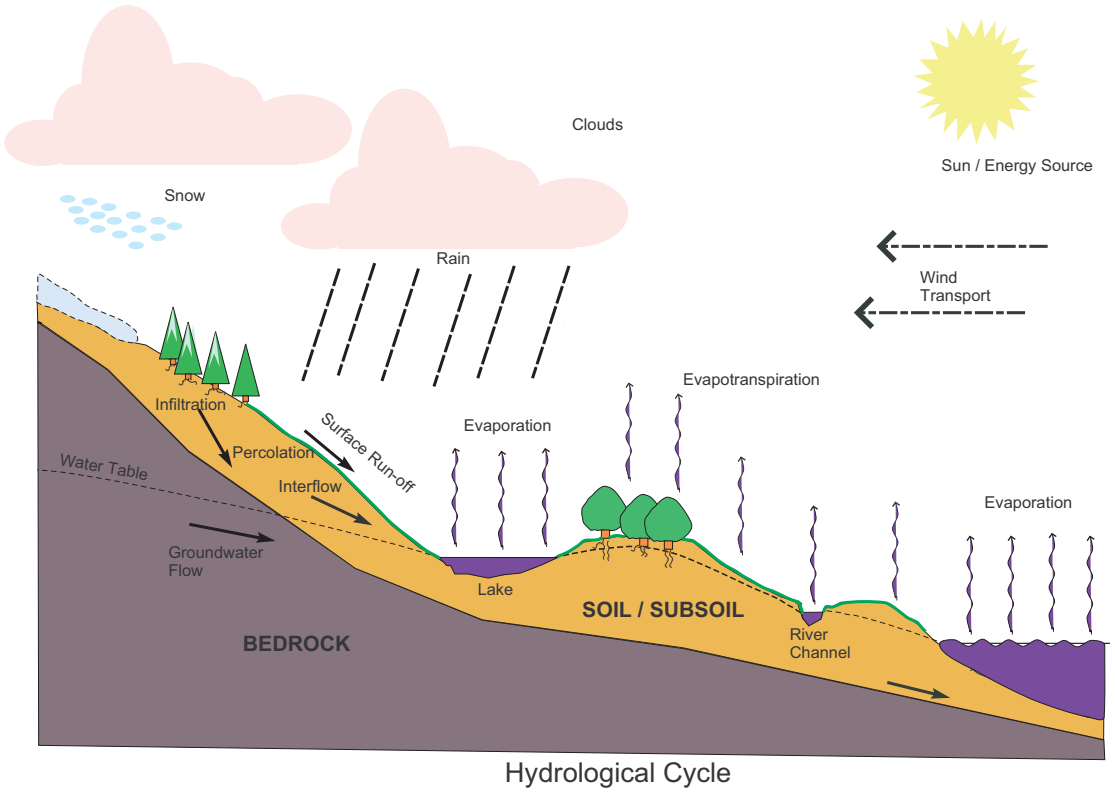

Fig. 1—Overview of the hydrological cycle.

the surfaces of leaves. In sub-zero temperatures precipitation may fall as snow or hail and may accumulate as a solid on the ground surface to thaw later.

Moving water has the potential to mobilise and transport material. When that material is harmful, the water is said to be contaminated. Moving air can also mobilise and transport material, but this paper focuses on water. Contaminants may be organic or inorganic, and they may be dissolved in the water or be in the form of particles. Sediment is a good example of the latter, but, in fact, other contaminants may be bound to the sediment particle's surface, or bound in a film covering its surface. A significant number of micro-organisms travel with sediment particles in flowing water (Schillinger and Gannon 1985; Mahler *et al.* 2000). Water moves these contaminants in a complex and dynamic manner. Pulses of sediment, micro-organisms and other contaminants (dissolved or particulate) mobilised by rainstorms are moved down the catchment, either over the ground surface or below it. In periods between rainstorms the catchment may still deliver contaminants in the base flows of rivers, but these have a higher fraction of dissolved material compared to particulates. These contaminants impact on the water-related ecology in a wide variety of ways. For instance, some contaminants contain elements required for growth, and so are effectively nutrients. P and N are typical examples, and an increase in their availability leads to excessive growth of plankton and algae typical of eutrophication (de Jonge *et al.* 2002) in surface waterbodies. Fine sediment can disturb incubation of salmon eggs (Greig *et al.* 2005), while coarser sediments in river beds may be reservoirs of micro-organisms (Searcy *et al.* 2006). In addition, changes to some physical properties of the water, such as water temperature, pH or salinity, may impact on dependent ecosystems.

The WFD has introduced a number of novel elements to water-resources management (Petersen *et al.* 2009), some of which are (i) a comprehensive and mandatory set of water-quality objectives focused on achieving good ecological status, (ii) a dynamic implementation strategy based on a six-year cycle (after the first), (iii) integrated water-resources management based on hydrologically distinct river basins, and (iv) a requirement for new implementation structures to manage WFD activities (e.g. government vs governance).

DATA COLLECTION AND MONITORING

Good-quality hydrometric data are the life-blood of hydrological research and practice. Hydrological systems cannot be brought into laboratories for refined measurements, nor can they be precisely controlled to generate specific test conditions for investigation. Hydrologists must study *in vivo* and make do with naturally occurring hydrological conditions. The main hydrological data types are discharge, precipitation, groundwater levels and evapotranspiration. A number of different agencies collect the data, each with different priorities and some with very specific foci.

DISCHARGE DATA

- Office of Public Works (OPW): The OPW has an extensive network of water-level recorders, mostly on the main rivers, from which discharge can be calculated. The OPW's main concern is flooding. Data can be obtained from their website or by contacting their hydrometric section.
- Environmental Protection Agency (EPA): The EPA operates a network of gauges that concentrate on the east and south-east of the country. Their main concern is water quality and low flows. Data can be obtained by contacting their hydrometric section.
- ESB: The ESB collects flow data for the rivers leading to their main hydropower installations. Data can be obtained by contacting their hydrometric section.
- Local authorities: Many local authorities collect flow data for specific purposes. They usually commission the EPA to arrange for the instrumentation and to collect the data.
- Research data: Various institutions, including universities and research institutes, collect flow data for research purposes. The data may usually be obtained by contacting the senior researcher involved.

PRECIPITATION/RAINFALL

- Met Éireann: Met Éireann owns and operates the Irish rainfall data-collecting network. It also operates two meteorological radars. It processes, analyses and reports on the data collected and undertakes associated research.
- Local authorities: Many local authorities collect rainfall data for specific purposes. They may collect the data themselves or commission a consultant to arrange for the instrumentation and to collect the data.
- Research data: Various institutions, including universities and research institutes, collect rainfall data in certain areas for very specific research purposes.

GROUNDWATER AND WELLS

- Geological Survey of Ireland (GSI): The GSI has a database of well logs, geology and groundwater levels. The GSI also produces maps of useful data, accessible through their website (GSI 2009).
- Research data: Various institutions, including local authorities, universities and research institutes, collect groundwater data in specific areas for research and management purposes.
- It can be expected that the EPA's monitoring data for groundwater levels will be made available to the public online.

EVAPOTRANSPIRATION

- Met Éireann produces potential-evaporation estimates from Class A evaporation pans at a small number of their stations. It can estimate potential evapotranspiration from measured meteorological variables.
- Teagasc measures evapotranspiration directly using lysimeters.

WATER QUALITY

The term 'water quality' relates to how suitable certain water is for its intended use; for example, human consumption, sustaining ecological systems, irrigated agriculture or industrial use. It is influenced by a wide range of physical, chemical and biological characteristics. The EPA assesses the water quality in Ireland's rivers, canals, lakes and coastal waters. The assessment is based on measurements of physical, chemical and biological indicators at a large number of locations. The results are published in a three-year review. The latest report (Clabby *et al.* 2007) covered the period 2004–6 and showed a slight increase in the total length of rivers classified as 'unpolluted', from 69.2% in 2001–3 to 71.4%. At the same time, the length of 'seriously polluted' rivers decreased from 6% to 5%. The biggest change was in the 'moderately polluted' category, which fell from 12.3% to 10.0%, while there was a slight increase in the length of 'slightly polluted' channel, from 17.9% to 18.1%. The number of lakes of 'satisfactory' standard increased to 85% of those examined—up from 82% in the period 2001–3. Interestingly, some of the improvement

in classification was ascribed to the effect of zebra mussel infestation. However, at the same time, the number of seriously polluted, 'hypertrophic' lakes increased to 15 (3.5% of total surface area of lakes examined) from 12 (1.4% of area). While the overall trend for rivers and lakes is encouraging, the trends for surface waterbodies in 'pristine' condition are not clear because, for rivers and lakes, these are included in the much bigger 'satisfactory' category. Faecal coliforms were detected in 58.5% of locations where groundwater samples were analysed for the 2004–6 status report. While this is an increase on the 49% of locations sampled for the 2001–3 report, there was a significant decrease in the number of samples with gross contamination (counts > 10/100ml), from 12% to 10.9%.

EFFECT OF THE WFD

The WFD, together with the subsequent Floods Directive (FD; 2007/60/EC; European Parliament and Council 2007), required larger amounts of accurate data over a wider spatial scale than any single project heretofore. These directives catalysed a large effort at improving and integrating the collection, processing and communication of hydrometric data. This included inspecting existing gauging sites, and improving and modernising some, with a particular emphasis on sites of direct relevance for the WFD and FD. Much of the OPW's discharge data and the EPA's data can be accessed via the internet (OPW 2009; EPA 2009). The EPA was given responsibility for preparing the monitoring programme for the WFD, which had to include data required for surveillance, operational and investigative purposes. The agency decided on the number and location of sampling sites and the methodology and frequency of data collection (EPA 2006). The programme covers a representative selection of rivers, lakes, groundwater, coastal and transitional waters, and canals (EPA 2006). It is intended to support the WFD's programme of measures (POM) and to help assess the impact of the measures. This is a vitally important task as it will inform future cycles of WFD activities and may enable the direct feedback required for adaptive-management approaches.

Many of the documents generated as part of the WFD activities can be obtained electronically from a single website (WFD Ireland 2009). This site has links to each of the river basin district (RBD) projects' websites, as well as to national and international sites with relevant information. It contains documents relating to public participation, the characterisation reports for the various waterbodies and the current versions of river basin management plans. This site also provides *Water maps*, a map viewer based on geographic information systems (GIS), showing many aspects of Ireland's waterbodies and their status.

The GSI also provides a public map viewer to allow access to their data sets, as well as an internet-based service for downloading spatial data sets.

HYDROLOGICAL MODELS

Models are simplifications of reality, constructed for a specific purpose. They can be:

1. Physical—typically scale models (e.g. flooding of a town) or models of some component of the system of interest (e.g. a single species of reed for a wetland).
2. Analogue—for instance, aquifers were once simulated in 2-D by applying voltages to an appropriately shaped sheet of material. Since water flow through an aquifer is a potential flow, like heat or electricity through a conductor, it is governed by Laplace's equation, and water, heat and electricity can be used as analogues of each other.
3. Numerical—given the computing power available on a single desktop, representing the governing equations of the phenomenon of interest by a digital approximation and solving the resulting equations is by far the most widely used type of model in practice.

Numerical models relate inputs to outputs through their interaction with parameters and internal model states. The purpose of the model determines the choice of inputs and outputs. Models can be further classified as lumped, semi-distributed or distributed on the basis of their spatial representation (Dooge and O'Kane 2004). A lumped model deals with averages or totals over the entire model domain, a distributed model takes account of the spatial variation in the quantities of interest, while a semi-distributed model treats the spatial variation by considering the system as a collection of simple, interconnected lumped systems. Each of these can be further sub-divided depending on how they represent the relationship between input and output. On the one hand, black-box models deliberately ignore any of the processes involved, and consist of general or empirical equations relating input and output—the unit-hydrograph method, regression models and annual P-export coefficient models are some examples. On the other hand, physically based models use equations

derived from physical laws, such as conservation laws and Newton's equations of motion, to represent the phenomenon of interest—examples include Richard's equation for infiltration, Darcy's equation for saturated groundwater flow and Manning's or Chezy's equation for free surface flows. In between these are conceptual models in which a simple analogue of the more complex reality is simulated. Examples are the cascade of linear reservoirs used to simulate surface run-off and the simple mixed tank used to simulate the effect of lakes or ponds on concentrations of some contaminants as they move along a river system. Models can be dynamic (in which variables can change with time) or steady-state (variables do not change with time), and they can be stochastic (random variations of some variables taken into account) or deterministic (randomness not taken into account).

Since the RBD teams are required to propose measures to address water and ecological issues, they must have tools to simulate the effect of every proposed measure for use in a decision-support framework (Irvine *et al.* 2005; Bruen 2008). Given the time frame involved, numerical models are the tools of choice. This has not led to a proliferation of models, but, because of cooperation and communication between RBD teams and delegation of some aspects of their work to individual RBDs, a relatively small number of models are being used. These tend to be empirical or conceptual and either lumped or semi-distributed. The value of fully distributed, physically based models in a management context has not yet been demonstrated (Nasr *et al.* 2007).

RESEARCH

A number of governmental organisations played key roles in initiating and sponsoring research to generate knowledge and methods for use in implementing the WFD.

ENVIRONMENTAL PROTECTION AGENCY

The EPA has included major WFD themes in its research programmes. The Environmental Research, Technological Development and Innovation (ERTDI) programme (2000–6) funded 70 projects in the area of water quality, including 17 large-scale and 12 medium-scale projects, at a budgeted cost of €39 million. The project topics span a wide scientific range (Table 1), but the concentration is obviously directed at filling knowledge gaps to support the early phases of the WFD, particularly the characterisation of waterbodies, the determination of reference conditions and the detailed study of specific threats to water quality. All the major elements of the hydrological cycle receive attention: rivers, lakes, groundwater and some of the least understood fluxes, such as recharge. Some of the larger projects were co-funded with other organisations, including Teagasc, the Marine Institute, the National Roads Authority (NRA) and COFORD (National Council for Forest Research and Development).

The subsequent Science, Technology, Research and Innovation for the Environment (STRIVE) programme (2007–13) is still in its early stages, with many projects directed at specific problem areas, such as groundwater fauna, alien species, priority substances and evaluation of responses.

GEOLOGICAL SURVEY OF IRELAND

Aquifers can be found in bedrock and/or subsoils, so the locations and characteristics of both are important for groundwater studies. The GSI produced a national bedrock map that grouped its 1,137 lithographic units into 27 rock unit groups (RUGs) likely to have different water-flow characteristics. Aquifers were delineated and classified into one of nine types on the basis of both RUG and information from the GSI's own wells and springs database. Prior to the WFD, the GSI had already been involved in mapping groundwater vulnerability on a county-by-county basis, and so had developed a methodology for characterising vulnerability based on soil (type, permeability and thickness) and bedrock (type and depth) information (Department of Environment and Local Government/EPA/GSI 1999). These vulnerability studies were combined with the soil and bedrock information from other counties to develop a national aquifer-vulnerability map for use with the WFD. Recharge characteristics—for example, whether it is point or diffuse—are taken into account, and special attention is paid to karst features that may provide a quick route for pollution to reach groundwater. The GSI also produces a regular, informative and highly regarded newsletter on hydrogeological matters.

NATIONAL ROADS AUTHORITY

The NRA supports research leading to a better understanding of any impacts of road infrastructure on water quality, either through road run-off (Desta *et al.* 2007) or from construction operations. Some of these projects intend to produce guidelines to inform future operations.

Table 1—ERTDI (2000–6) projects relating to hydrology (reports available on the EPA website).

Hydrology-related projects
Impact assessment of highway drainage on water quality
Eutrophication from agricultural sources—P and N
Forestry and environment impacts addressing water quality and biodiversity
Development of a generic tool for flushing-study analyses
Development of a methodology for the characterisation of unpolluted groundwater
Development of a methodology for the characterisation of a karstic groundwater body, with particular emphasis on the linkage with associated ecosystems, such as turloughs
Hydromorphology of rivers
Assessment of the mathematical modelling in the implementation of the WFD in Ireland
Characterisation of reference conditions and testing of typology of rivers
Recharge and groundwater vulnerability
Pilot river basin
Test of different ecological responses to nutrient loads of soft- and hard-water lakes
Creation and assessment of digital spatial-modelling techniques for the management of lake water quality in the Lough Leane and Lough Feeagh catchments
Improved water-quality data analysis and interpretation
Integrated GIS and neuro-fuzzy analysis for use in RBD management
Investigation into the effective distribution of on-site wastewater effluent into percolation areas and the treatment performance of sandy subsoils and constructed wetlands
Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in two contrasting instrumented catchments in Ireland (ILLUMINATE)
WFD applied testing and evaluation fellowship
Decision-support systems for the ecological assessment of rivers
Environmental impact of agricultural practices in relation to nutrient-management planning, to be carried out under the auspices of the North–South initiatives for cooperation in the area of the environment
Design of an Internet-accessible, real-time water-quality monitor
Bathing Water Directive study
Analysis of water resources under future climate scenarios, coupled with projected land-use changes for selected river basins in Ireland
Pollution assessment of the Tolka River estuary

MARINE INSTITUTE

The Marine Institute is involved in the implementation of the WFD, particularly, but not exclusively, in relation to coastal waters. As many of the contaminants reaching estuaries and the near-shore environment are carried there by rivers, many coastal issues must be addressed on land. The institute's hydrometric survey provides essential bathymetric information for coastal modelling, and the institute is involved in research projects related to climate change and real-time sensing, such as SmartBay (Marine Institute 2009).

WFD WORKING GROUPS

A number of working groups were set up to consider and report on specific aspects of the WFD or specific problem areas. These groups generally had a wide membership and consisted of members of the RBD teams, as well as academic and other interested parties. Some of these groups are described briefly below.

HYDROMETRY

Reliable hydrometric data are essential for water-resources planning or management. A considerable amount of hydrological preparatory work was required to prepare for the activities of the individual RBD projects. The WFD Hydrology Committee advised the EPA in the delineation of the boundaries of the RBDs in the field, and in reconciling them with OPW drainage maps and digital terrain products. A backlog of water-level charts was digitised under contract, and a web-based system for publishing hydrometric information (EPA 2009) was implemented. Individual gauge sites were

inspected, and improvements were recommended for identified problems. Guidelines were developed for the construction of new gauging sites (MacCarthaigh and Bree 2007), and a monitoring programme was devised to include the biological (79 sites) and chemical water-quality analysis needed to meet the requirements of the WFD, OSPAR convention (19 sites) and Exchange of Information Directive (77/795/EEC) (4 sites). A methodology for deriving flow-duration curves for natural catchments was developed, and software was commissioned to estimate the flow-duration curves for all gauges to be used in the WFD work. The main factors influencing such curves were (i) rainfall, (ii) presence of 'made' land, (iii) presence of karst, (iv) soil characteristics, (v) subsoil characteristics and (vi) presence of lakes or reservoirs.

The inadequacy of evaporation and evapotranspiration data was identified as an important and urgent limitation; however, despite considerable debate, a clear plan for addressing the issue has not yet emerged.

GROUNDWATER

The WFD defines groundwater bodies as (i) groundwater from which significant amounts of water can be extracted and/or (ii) groundwater in contact with ecosystems. They consist of an aquifer with connected spaces that can contain and transmit water. These spaces may be gaps between grains of sand gravel or weathered or eroded granular material (intergranular permeability), or they may be connected fractures in rock (fissure permeability) or tunnels dissolved by flowing water in the rock (karst). The nature of the permeability has a significant role in determining the amount of water moving through the aquifer and its ability to convey and attenuate contaminants.

Following on from earlier work by the Irish WFD Working Group on Groundwater (River Basin Districts 2005), Misstear and Brown (2008) and Misstear *et al.* (2009) studied in detail the vertical aquifer recharge in four very different aquifer settings. They concluded that subsoil permeability had the largest influence on the amount of recharge and that subsoil type and thickness and the ability of the aquifer to accept additional recharge were also influences. They estimated a range of recharge coefficients for the major aquifer settings (Table 2). Recharge coefficients are closely related to aquifer vulnerability, as both are heavily influenced by subsoil permeability and thickness and, considering the nature of the hydrological cycle (Fig. 1), are expected to vary inversely as run-off coefficients. Comparison of intensive modelling of the Kildare aquifer using MODFLOW with measured borehole data suggested that there was a significant time lag between the rainfall reaching the ground surface and recharge reaching the aquifer. Bruen (1995) has demonstrated such lags in modelling moisture flows in an idealised homogeneous, well-drained loam soil forced by rainfall and potential evaporation, for an EU research project (Fig. 2), which also showed the reduction with depth of the variability of the moisture content.

A less studied topic in Ireland is the exchange of water between aquifers and rivers. Coxon and Drew (2000) studied the special case of surface water and groundwater interactions in karst, and Bruen and Osman (2004) and Osman and Bruen (2002) studied methods for modelling the loss of water from a river to an aquifer in an alluvial setting. The latter team showed that, in certain cases, the loss of water from the river to the aquifer could be seriously underestimated by existing methods that neglected the formation of unsaturated zones and higher soil suctions in the recharge area, and they produced a model that improved on the existing MODFLOW code. River–aquifer interaction complicates the determination of source protection zones (Environment and Heritage Service 2001). Quantitative approaches to estimating river–aquifer exchanges were reviewed by Rushton

Table 2—Recharge coefficient estimates (source: Misstear and Brown 2008).

Location	*Aquifer setting*	*Recharge coefficient range*
Kildare aquifer (Curragh)	High-permeability gravels overlain by thin layer of till	80–85%
Callan–Bennetsbridge	Moderate-permeability subsoil areas only	41–54%
Callan–Bennetsbridge	Mixture of high-, medium- and low-permeability subsoils	36–60%
Galmoy	Moderate-permeability subsoils	55–65%
Knockatallon	Low-permeability subsoils	Definitely < 17% and possibly < 5%

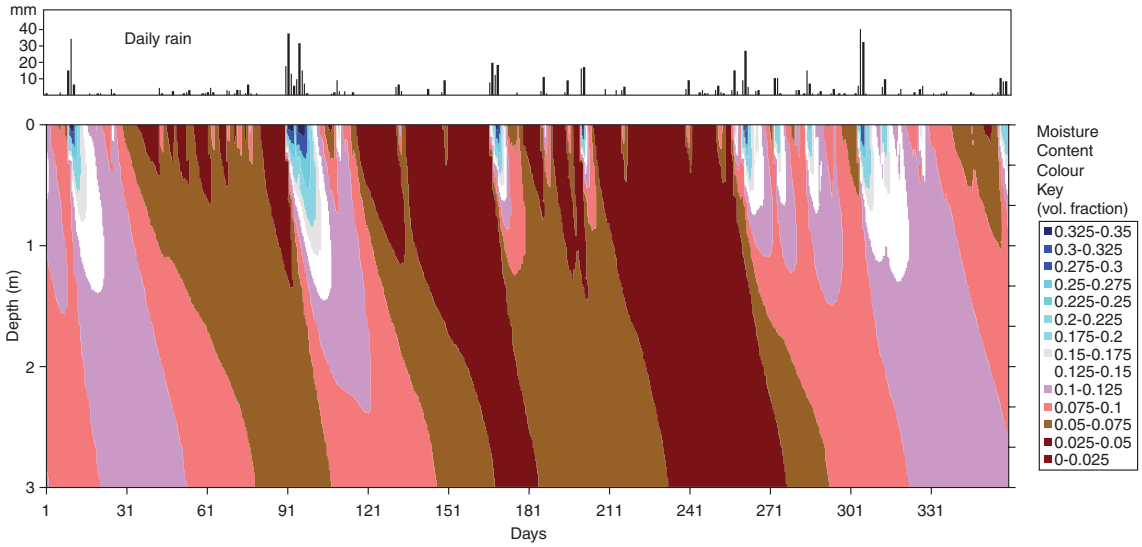

Fig. 2—Simulation for a year of soil-moisture variation with depth in a well-drained, homogeneous, 3m-deep loam soil.

(2007), and ecological implications were reviewed by Kirk (2006). When water moves from aquifer to river, it contributes mostly to the base flow. Uncertainties about the extent of contamination of surface waters by aquifers (e.g. with pesticides) are still unresolved (Northern Ireland Environment Agency 2008).

CONTRIBUTION OF GROUNDWATER TO SURFACE WATER

The South Western RBD led a team that studied the magnitude of the contribution of groundwater to river flows, and to baseflows in particular. This study may also contribute to understanding the effects of groundwater abstractions on river flows. The initial debate concerned the precise definition of the various flow components and how to distinguish between their individual influences on flow and water quality. Five flow pathways from catchment to river were identified: (i) overland flow, (ii) interflow, (iii) shallow groundwater flow, (iv) deep groundwater flow and (v) fissure and conduit flow. However, in practice it was possible to quantify only three components: (i) overland flow, (ii) intermediate flow and (iii) deep groundwater flow. A particular focus of the discussion was the differences in pathways and water quality between flow through productive (faster and deeper, with less time in contact with rock) and unproductive (slower and shallower, with more time in contact with rock) aquifers (Fig. 3). The team produced a useful literature review of hydrograph-separation methods and applied three methods to data from seven catchments covering a range of Irish conditions. The methods tested were (i) master recession curve analysis, to identify the deep groundwater flow component; (ii) Broughton's two-parameter method; and (iii) the US Soil Conservation Service's unit-hydrograph method.

The study also fitted the lumped, conceptual rainfall-runoff model NAM (Nedbør-Afstrømnings-Model) to data from the test catchments. Table 3 summarises the various results for the test catchments. The difficulty with this study is underlined by the variation in the results for each catchment, some of which can be explained by differences in the flow components involved in each method; for example, the unit-hydrograph method would lump fast-responding karst flows together with surface run-off as a combined 'quick response' signature. A significant feature of the study was a procedure for regionalising four of the parameters of the NAM model so that it could be applied to ungauged catchments. These parameters were:

1. Coefficient for overland flow (CQOF): The NAM model simulates overland flow as primarily determined by soil-storage state (the Dunne mechanism), and if the model determines that overland flow is to occur, the fraction of the net precipitation that becomes overland flow is proportional to the product of the parameter CQOF and a soil-moisture index. The value of CQOF is primarily based on aquifer type, modified by consideration of the catchment soils and slope. In areas dominated by gravels values range from 0.2 (far from a river) to 0.6

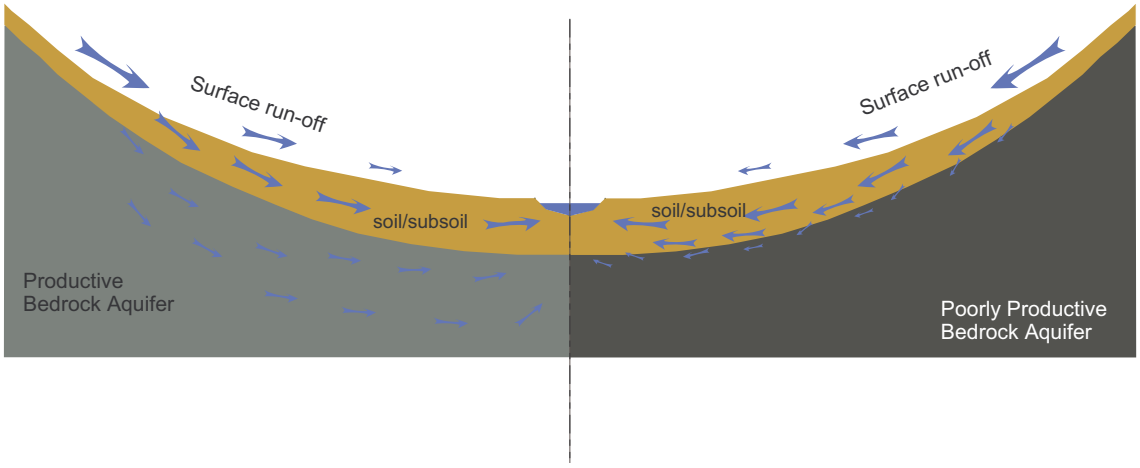

Fig. 3—Partial conceptualisation of the differences in flow paths between a productive and poorly productive aquifer (adapted from an Irish WFD Groundwater–Surface Water Interaction Group report).

(close to a river), but values range from 0.5 to 0.9 for other aquifer types.

2. Capacity of the surface store (U_{max}): This is determined primarily by vegetation and surface topography. Suggested values vary from 8 to 25mm.
3. Intermediate-flow time constant (CKIF): This is the lag time of the faster subsoil response, and catchment slope has a large influence on its value. It is interesting that some index of catchment size, such as area or length of flow path, was not used in determining its value, as

Table 3—Identification of deep groundwater flow, intermediate flow and overland flow for the priority catchments (source: Irish WFD Groundwater–Surface Water Interaction Group).

Pilot catchment	*Hydrogeological scenario*	*Deep groundwater flow*				*Intermediate flow*	*Overland flow*	
		NAM (mm y^{-1})	*MRC (mm y^{-1})*	*Permeability calculations (mm y^{-1})*		*NAM (mm y^{-1})*	*NAM (mm y^{-1})*	*UH (mm y^{-1})*
Boro	Rf volcanic aquifer (mixed scenario: Rf/Ll/Pl)	240	388 (deep + other component)	238	271	217	231	215
Bride	'Southern synclines' scenario (Ll and Rkd)	200	537 (deep + other component)	183	219	269	352	336
Deel	Ll limestone	159	323 (deep + other component)	91	201	210	120	168
Owenduff	Pl poorly productive	128	441 (deep + other component)	83	173	318	1,322	1,074
Ryewater	Ll limestone	121	110	91	201	85	171	191
Shournagh	Ll Old Red Sandstone	220	321 (deep + other component)	183	219	205	383	357
Suck	Karst	171	234	–	–	362	124	354

Ll = bedrock aquifers that are moderately productive only in local zones; MRC = master recession curve; NAM = hydrological model; Pl = bedrock that is generally unproductive except for local zones; Rkd = regionally important karst aquifers dominated by diffuse flow; Rf = fissured bedrock aquifers; UH = unit-hydrograph method.

would be expected for a lag time for surface flows.

4. Deep groundwater-flow time constant (CKBF): This is the lag time of the groundwater (or base flow) response to recharge, and it is determined primarily by aquifer type. Again, it is interesting that no index of catchment size was used in determining its value.

The other parameters—the capacity of the soil-moisture store and the various flow-generating thresholds—were fixed at values determined by prior experience. This procedure was tested by applying it to an independent set of catchments, and it provided good results for both R^2 values for the complete hydrographs and water balance for most of the catchments.

TURLOUGHS

Turloughs are surface depressions in karst that are inundated annually. The water-level variations can be considerable, causing local flooding in winter and drying out in summer, and so turloughs form a special habitat. Flooding associated with turloughs has been studied (e.g. OPW 1998). Many turloughs are designated as Special Areas of Conservation (SACs). Guidance on catchment delineation and risk assessment for turloughs was developed by a turlough subcommittee of the Irish Working Group on Groundwater. They identified two types of flow system: (i) epi-karst, in which infiltrated rainfall flows to the turlough through a relatively thin upper layer of weathered karst; and (ii) mixed flow, in which water can reach the turlough through a variety of pathways, including through epi-karst and flows through deeper solution tunnels. Kilroy *et al.* (2005) point out that the high degree of surface water and groundwater interaction in turloughs complicates the delineation of the contributing area, which may vary with time, and thus the vulnerability assessment. Multivariate analysis by Visser *et al.* (2006) suggests that turlough types do not split readily into a small number of categories, but that there is a continuum of typologies between dry and wet, which should be reflected in the management approach.

WETLANDS

Wetlands are distinct vegetated areas with standing or slowly moving water. They may be isolated from other waterbodies, but they are usually connected with groundwater or a surface waterbody, or both. The hydrological connections may be intermittent; for example, a wetland on a floodplain that is occasionally inundated over the surface by a flood in the river while being continuously connected with the river through a soil-moisture continuum. Krause *et al.* (2007) developed an ecohydrogeological tool for the type-specific assessment of vulnerability and risk as part of a Scottish and Northern Ireland Forum for Environmental Research (SNIFFER) project (see 'Other external inputs' below). This tool explicitly considers the various hydrological pathways and controls influencing the flow of water into the wetland.

LAKES

The WFD considers lakes with surface areas greater than 50ha, lakes that are designated as SACs and lakes from which water is abstracted. The selection process in the Republic of Ireland yielded a list of 745 lakes to be considered. They receive water from direct precipitation, surface run-off and subsurface flows from surrounding lands, inflows from streams and, possibly, inflows from groundwater. Water losses occur from direct evaporation, from outflow through the lake outlet and possibly from movement to surrounding soils or groundwater. Because of these multiple hydrological connections, lakes are subject to a wide variety of pressures. From a hydrological point of view, the lake provides storage with a negative-feedback loop between water level and outlet hydraulics, providing a stabilising influence on water levels. In lakes, waters from the various inflows and their contaminants are mixed, and suspended particles may settle, so this can have a beneficial effect on downstream water quality. Shallow lakes may be completely mixed by wind-induced waves and currents, while deeper lakes may be stratified with very different conditions at the bottom and surface.

PEATLANDS

A study of peatlands was coordinated by the Shannon International RBD (ShIRBD) as 11% of its catchment area is peatland. Harvesting of peat at an industrial scale requires the construction of a new, efficient drainage system to dry out the areas to be harvested. The improved drainage increases the run-off rates from the area and shortens the time of concentration. This has implications for downstream flood risk, but it has not been extensively studied. However, water-quality issues are of major concern since the amounts of sediment and nutrients carried in the water will increase. Silt lagoons or ponds are generally constructed to retain peat particles by allowing them to settle, and so reduce the downstream impact. Typically, the lagoons are cleaned twice per year. The ShIRBD investigation

(ShIRBD 2008) confirmed that the silt lagoons considerably reduce silt and P loads, although there are occasional periods in which guideline standards are exceeded. However, ammonium concentrations are generally high in the outflows from the lagoons. There is considerable debate on the future use of worked peatlands once harvesting stops. One possible use is as a flood-attenuation area to reduce the peak discharges of floods in local rivers. The key hydrological issues are (i) the provision of a storage area for the flood waters; (ii) the provision of a suitable hydraulic arrangement, natural or man-made, to limit flows in the river; and (iii) water-quality issues arising from the change in inundation regime.

HIGHWAY DRAINAGE

Bruen *et al.* (2006) and Desta *et al.* (2007) reported on a study of the impact of road-drainage systems on water quality in receiving streams and on ecological conditions. They instrumented four separate road catchments with similar traffic flows but with different drainage arrangements, including grass verges, French drains and kerb-and-gully designs. Their water-balance calculations suggested that, in existing situations, not all of the run-off reaches the intended surface water receptor, and the implication is that some of this water may reach groundwater. The run-off contaminants included suspended solids; heavy metals; hydrocarbons, including polycyclic aromatic hydrocarbons; chlorides; nitrates; and P. However, methyl tertiary butyl ether, a carcinogenic fuel additive of some concern, was not detected in the study. The study showed that a wetland system performed well in reducing these contaminants and also that French drains allowed some of these contaminants to migrate into the subsoil, having a beneficial impact on the quality of surface water discharges. Despite some elevated heavy-metal concentrations in aquatic vegetation near discharge points for road run-off, the data show no statistically significant difference between upstream and downstream concentrations in vegetation or in macroinvertebrates and no measurable impact on fish. However, Irish traffic conditions are near the lower threshold for such effects detected in European and US highways.

COMMUNICATION AND CONSULTATION

An important element of the WFD is consultation with stakeholders. For the WFD to be effective, stakeholders must understand the basic concepts and communicate any preferences or concerns they may have. To assist with this, a joint Ireland–UK task team commissioned a set of images that could be used to communicate the key concepts relating to groundwater and made them public through a website (Daly *et al.* 2006). The resulting images (SNIFFER 2009a) also helped to promote a common terminology amongst the various professionals dealing with hydrogeological concepts.

Each RBD has an advisory council of representatives of stakeholder groups, including elected local authority councillors. These councils were kept informed of the activities involved in characterising waterbodies and formulating POMs, and they had an opportunity to comment on this work. Roadshows were organised to bring information to the public, and visits to local schools informed children of the WFD activities.

INTERNATIONAL LINKS

INTERNATIONAL HYDROLOGICAL PROGRAMME

The International Hydrological Programme (IHP) is a UNESCO (United Nations Educational, Scientific and Cultural Organization) scientific cooperative programme in water research, water-resources management, education and capacity-building. Similarly, the International Commission on Irrigation and Drainage (ICID) is a scientific organisation dedicated to enhancing the worldwide supply of food and fibre for all people by improving water and land management and the productivity of irrigated and drained lands. The Irish National Committees of the IHP and ICID liaise with UNESCO and the International Association of Hydrological Sciences on hydrological matters. The committees consist of representatives from all governmental organisations with a major interest in water matters, representatives from universities with major hydrological programmes and cognate representatives from Northern Ireland. The committees were quick to react to a hydrological-information need by making the WFD the subject of their annual hydrology seminar in 2000. As well as technical papers from Ireland, the seminar's presentations included a number of UK contributions and one from Portugal (Irish National Committees of the IHP and ICID 2009). Subsequent seminars were directed at specific areas of concern for the WFD, including water-resources management (2002), monitoring and modelling (2004), climate change

(2006) and GIS in hydrology (2007). In addition, the IHP committee has provided comments on draft documents and has issued technical advice on specific hydrological issues.

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS

The Irish Group of the International Association of Hydrogeologists (IAH) is the focus point for hydrogeological discussion in Ireland. The group organises a regular series of technical discussion meetings, many on topics of WFD interest and many with guest speakers from abroad, and also organises an annual symposium with many sessions of direct relevance to the WFD. For instance, the group's 25th-anniversary conference in 2005 had a special session on River Basin Development, the 2006 meeting concentrated on sustainable urban drainage systems, the 2007 meeting had sessions on groundwater pressures and management tools, and the theme of the 2008 meeting was 'Groundwater—a resource at risk'.

OTHER EXTERNAL INPUTS

The Irish IHP committee and IAH group provide a formal link with international organisations and knowledge. However, many other ad hoc links have developed, in terms of both research and management. The SNIFFER research programme includes many projects addressing WFD issues (SNIFFER 2009b). In addition, each of the RBD projects is implemented by different teams of consultants. In each RBD the team has members from abroad and, in some cases, has links to the European Commission through its INTERREG programme.

OTHER DIRECTIVES

The implementation of the FD is relevant to the WFD. Although flood mitigation is mentioned in the WFD's preamble as one of its objectives, and also as (i) implicated in a failure to meet the required good status or as (ii) being adversely affected by morphological changes required to achieve good status, it does not receive a corresponding degree of attention in its implementation. However, the recent FD deals specifically with the issue and requires that areas at risk of flooding be identified and that appropriate management plans be developed. The OPW is responsible for implementing the FD. Although water-quality issues are a major concern at low flows, and flooding is a concern at high flows, there is still considerable overlap between the hydrology involved, particularly in terms of data collection and flow modelling. This alone justifies some integration at the level of management plans, at the very least, to avoid mutually exclusive objectives and to achieve synergies at all levels.

CONCLUSIONS

The activity required to implement the WFD has delivered major benefits to the practice of hydrology in Ireland:

1. Major increase in the amount, quality, currency and availability of hydrologically relevant data sets (topography, catchment delineation, land use, soils, bedrock, flows, rainfall).
2. Major review, quality control and updating of hydrometric network measuring discharge, rainfall and water-level data, with the one exception being evapotranspiration, as Ireland's data are inadequate in this area. Of particular significance are the quality-controlled data sets generated by studies undertaken by the various working groups set up by the RBDs.
3. Identification of important water- and ecology-related knowledge gaps, and some progress in addressing them.
4. Major review of the condition of Ireland's waterbodies and a detailed assessment of major threats to their water-quality status.
5. An increase in the understanding of the complexities of Ireland's hydrological setting, particularly in relation to groundwater.
6. An understanding of the power and limitations of models as tools.
7. A significant increase in interaction, communication and mutual understanding between surface water and groundwater hydrologists, between numerical modellers and field hydrologists, and between hydrologists and biologists/botanists. While this may be the most intangible of the recent developments sparked by the WFD, it may yet prove to be the most significant and enduring.

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