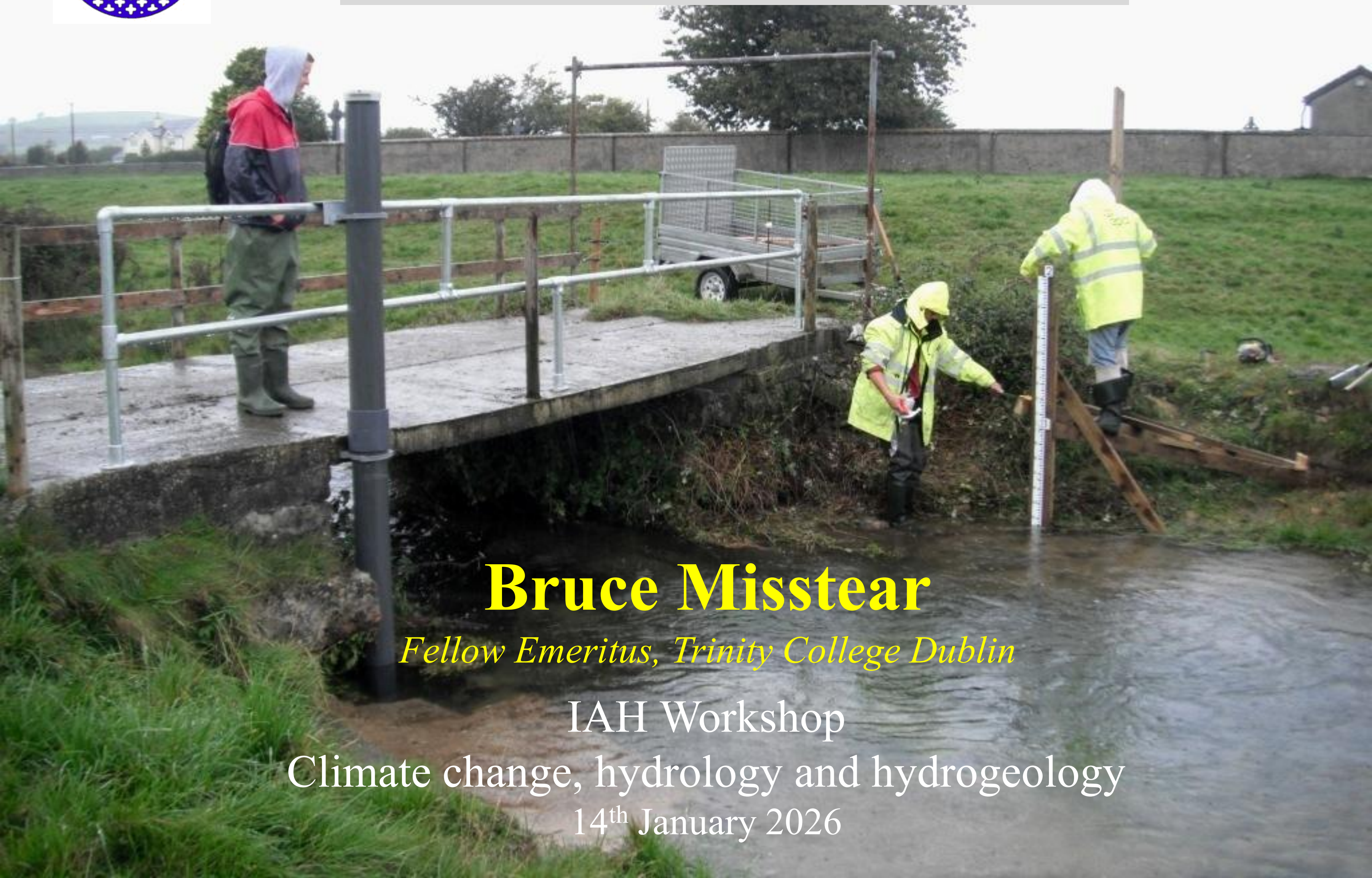
Groundwater recharge



Bruce Misstear

Fellow Emeritus, Trinity College Dublin

IAH Workshop

Climate change, hydrology and hydrogeology

14th January 2026

Recharge estimates are needed to:

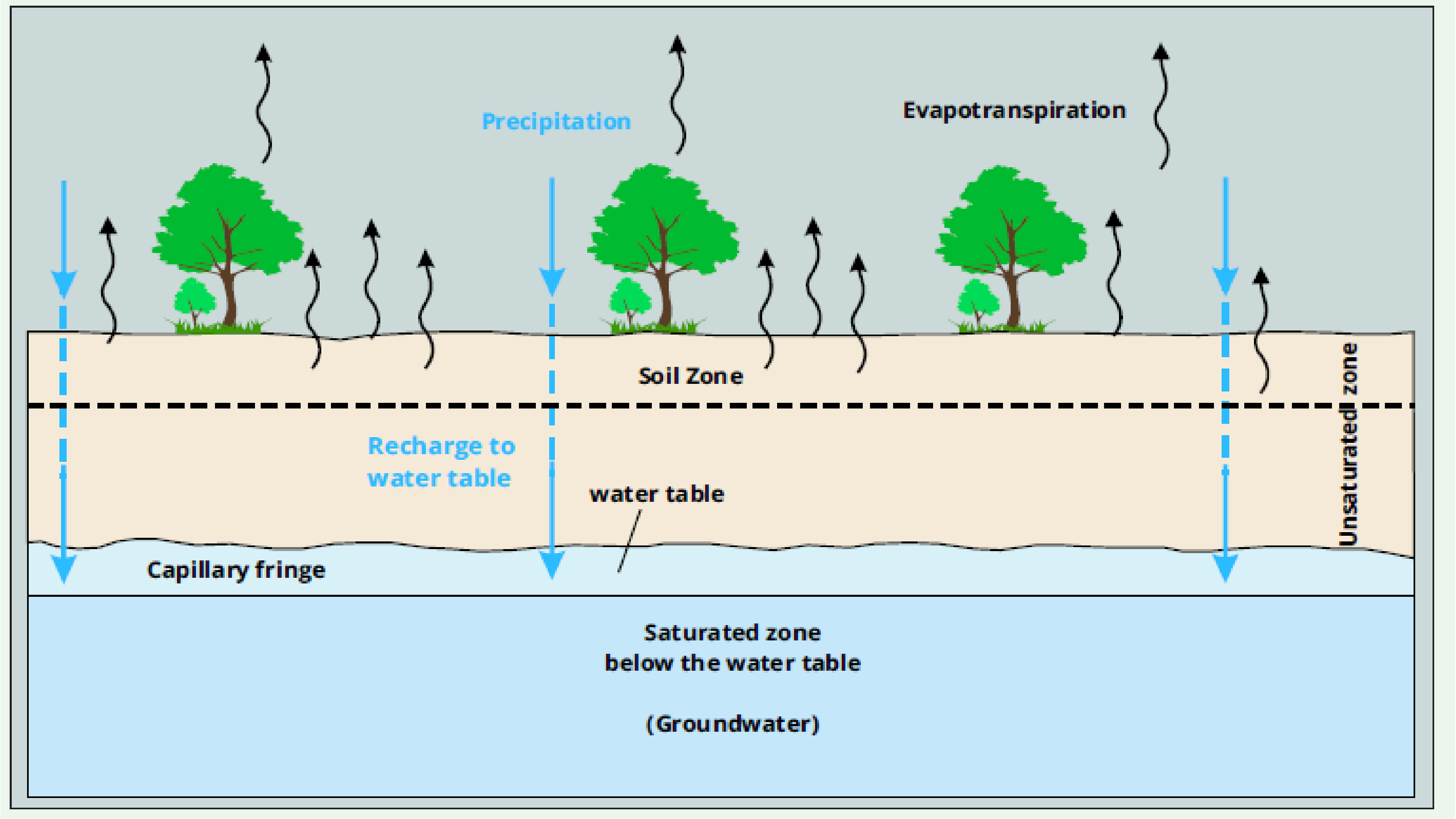
- quantify groundwater resources within River Basin Districts and Groundwater Bodies
- issue abstraction licences
- assess baseflows and contributions to wetland habitats (groundwater-dependent terrestrial ecosystems)
- assess groundwater vulnerability
- delineate Source Protection Areas
- identify implications for groundwater resources of changes in land use and/or climate

What is recharge?

- Recharge can be defined as: ‘downward flow of water reaching the water table, adding to groundwater storage’ (Healy, 2010)

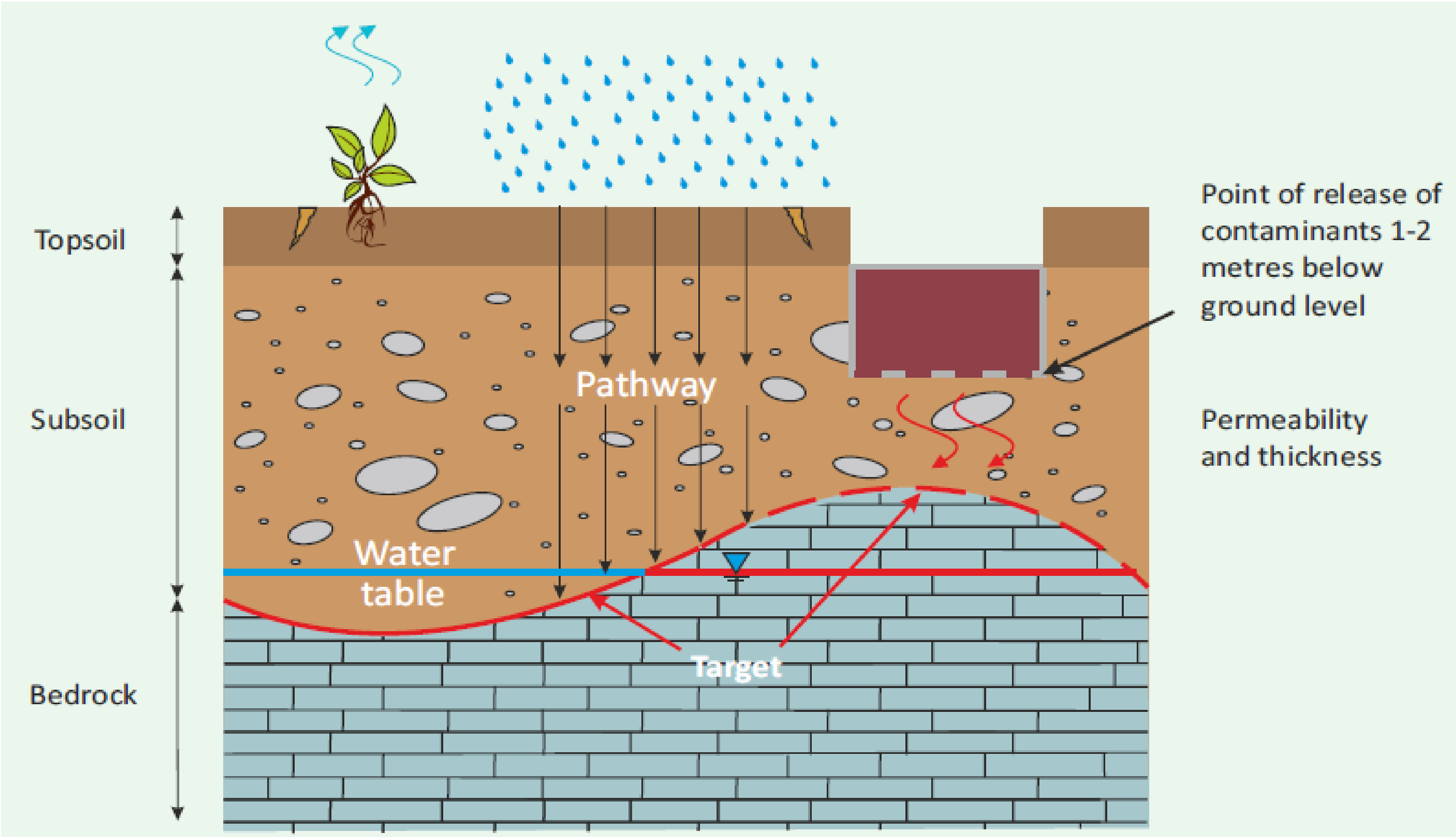
- Types of recharge:
  - Direct (diffuse)
  - Indirect (point, focused)

Groundwater recharge



(USGS image)

Groundwater vulnerability concepts in Ireland



(Diagram prepared by GSI; in Misstear 2023)

Factors influencing recharge:

- precipitation
- topography
- vegetation and evapotranspiration
- soil and subsoil types
- flow mechanisms in unsaturated zone
- bedrock geology
- available groundwater storage
- presence of influent rivers
- presence of karst
- irrigation schemes
- urban areas

Approaches to recharge assessment

(see Section 2.6 in Misstear et al. 2017)

- Inflow estimation e.g.:
  - Soil moisture budgeting
  - Darcy flux calculations
  - Recharge coefficients
  - Tracers
- Aquifer response analysis
  - Well hydrograph analysis
  - Darcy throughflow calculations
  - Dupuit-Forchheimer calculations
- Outflow estimation
  - River baseflow analysis
  - Measuring spring flows
- Catchment water balance and modelling

Inflow estimation (direct recharge)

- soil moisture budgets
- infiltration coefficients (recharge coefficients)
- soil moisture flux approaches
- lysimeters
- tracers
- direct observations

These methods mainly provide estimates of potential recharge

We can also estimate inflows from rivers that lead to indirect recharge

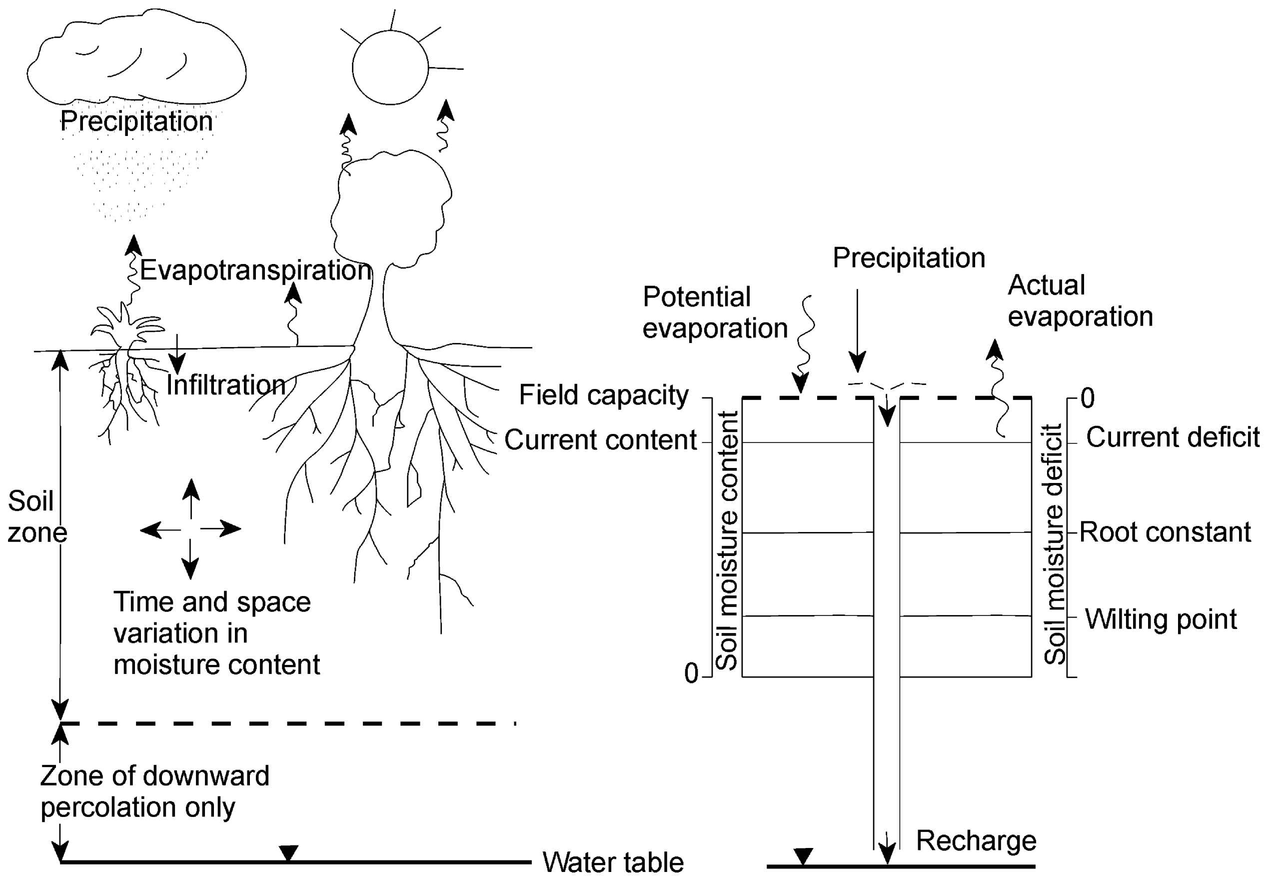
Indirect (focused) recharge

Indirect recharge includes:

- Infiltration from losing streams
- Infiltration of runoff in arid areas
- Infiltration from swallow holes in karst limestones
- Infiltration from leaking pipes, sewers etc
- Irrigation return flows

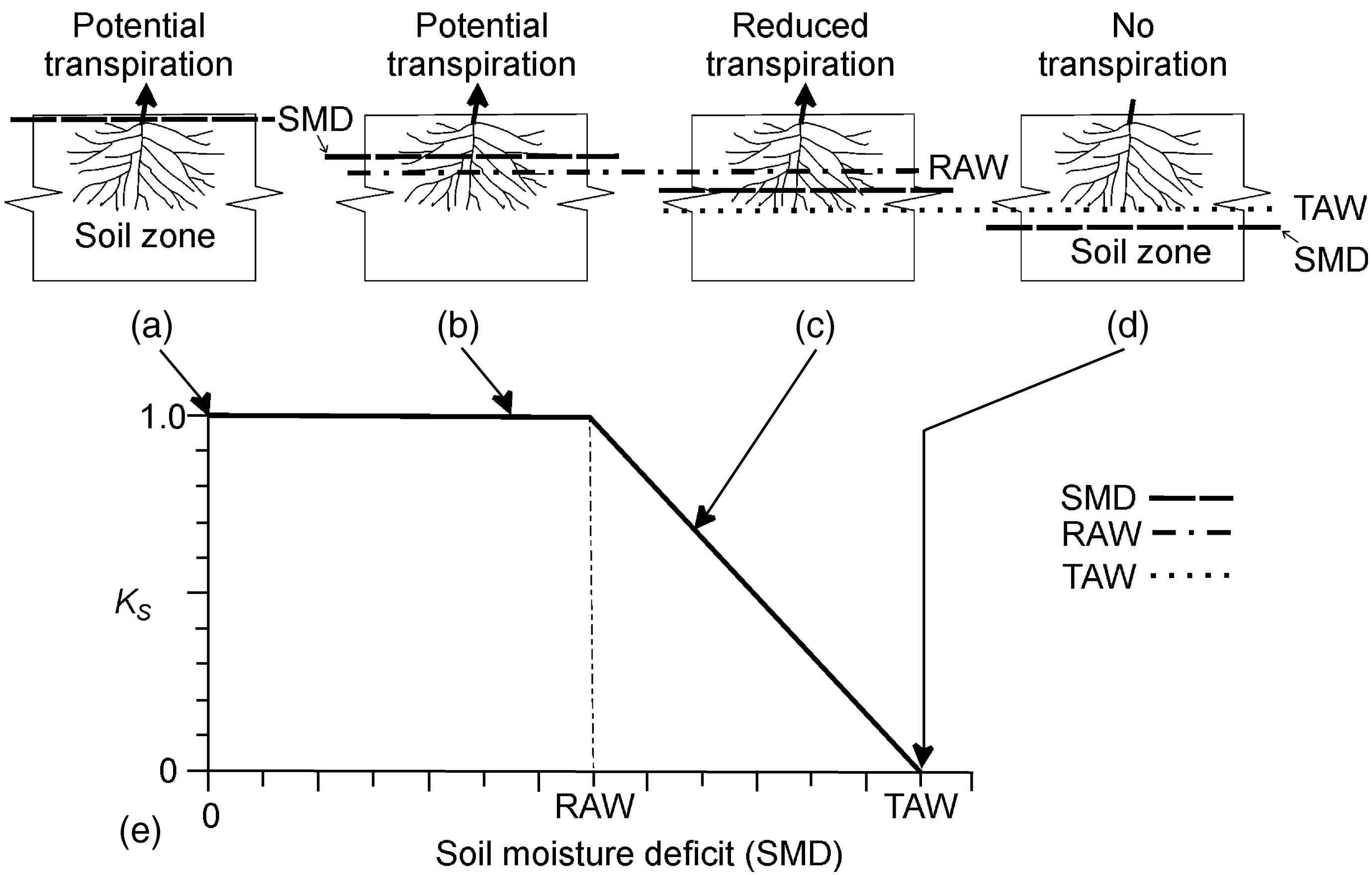
Direct recharge: soil moisture deficit concepts

(Image from Misstear et al. 2017, based on Lerner et al. 1990)



Evapotranspiration reduces when the soil moisture deficit increases beyond the readily available water

(Image from Misstear et al. 2017, based on Rushton 2003)



Recharge coefficient: the proportion of effective rainfall that forms recharge

Table 2. *Recharge coefficients for different hydrogeological settings (updated and modified from IWGGW 2005b and Misstear et al. 2009a). Descriptions of the different GIS layers used to characterize the hydrogeological settings and estimate groundwater recharge are given in the text*

Groundwater vulnerability category	Hydrogeological setting	Recharge coefficient (RC)		
		Minimum (%)	Inner range (%)	Maximum (%)
Extreme (X or E)	1.i Areas where rock is at ground surface	30	80–90	100
	1.ii Sand or gravel overlain by 'well-drained' soil	50	80–90	100
	1.iii Sand or gravel overlain by 'poorly drained' (gley) soil	15	35–50	70
	1.iv Till overlain by 'well-drained' soil	45	50–70	80
	1.v Till overlain by 'poorly drained' (gley) soil	5	15–30	50
	1.vi Sand or gravel aquifer where the water table is ≤3 m below surface	50	80–90	100
	1.vii Peat	1	15–30	50
High (H)	2.i Sand or gravel aquifer, overlain by 'well-drained' soil	50	80–90	100
	2.ii High permeability subsoil (sand or gravel) overlain by 'well-drained' soil	50	80–90	100
	2.iii High permeability subsoil (sand or gravel) overlain by 'poorly drained' soil	15	35–50	70
	2.iv Sand or gravel aquifer, overlain by 'poorly drained' soil	15	35–50	70
	2.v Moderate permeability subsoil overlain by 'well-drained' soil	35	50–70	80
	2.vi Moderate permeability subsoil overlain by 'poorly drained' (gley) soil	10	15–30	50
	2.vii Low permeability subsoil	1	20–30	40
	2.viii Peat	1	5–15	20
Moderate (M)	3.i Moderate permeability subsoil overlain by 'well-drained' soil	35	50–70	80
	3.ii Moderate permeability subsoil overlain by 'poorly drained' (gley) soil	10	15–30	50
	3.iii Low permeability subsoil	1	10–20	30
	3.iv Peat	1	3–5	10
Low (L)	4.i Low permeability subsoil	1	5–10	20
	4.ii Basin peat	1	3–5	10
High to Low (HL)	5.i High predicted permeability subsoils (sand or gravels)	30	80–90	100
	5.ii Moderate permeability subsoil overlain by well-drained soils	35	50–70	80
	5.iii Moderate permeability subsoils overlain by poorly drained soils	10	15–30	50
	5.iv Low permeability subsoil	1	5–10	20
	5.v Peat	1	5	20

Note that recharge to bedrock aquifer classes Pu and Pl is limited to 100mma^{-1}, and to Ll aquifers is limited to 200mma^{-1}. Areas of 'made ground' are assigned a recharge coefficient of 20%. Before full national groundwater vulnerability coverage was achieved in 2012, in unmapped regions the Extreme and High to Low vulnerability categories were used.

(Hunter Williams et al. 2013)

Methodology for preparing Irish recharge maps using estimates of effective rainfall, recharge coefficient and aquifer storage recharge caps

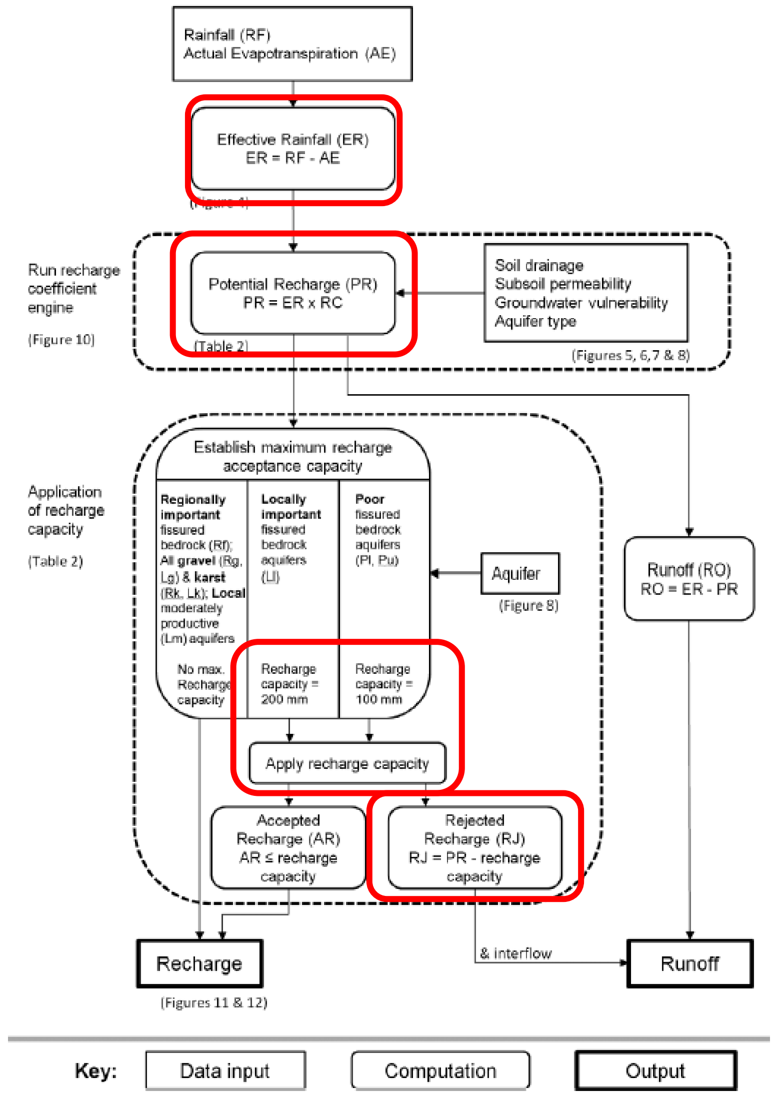
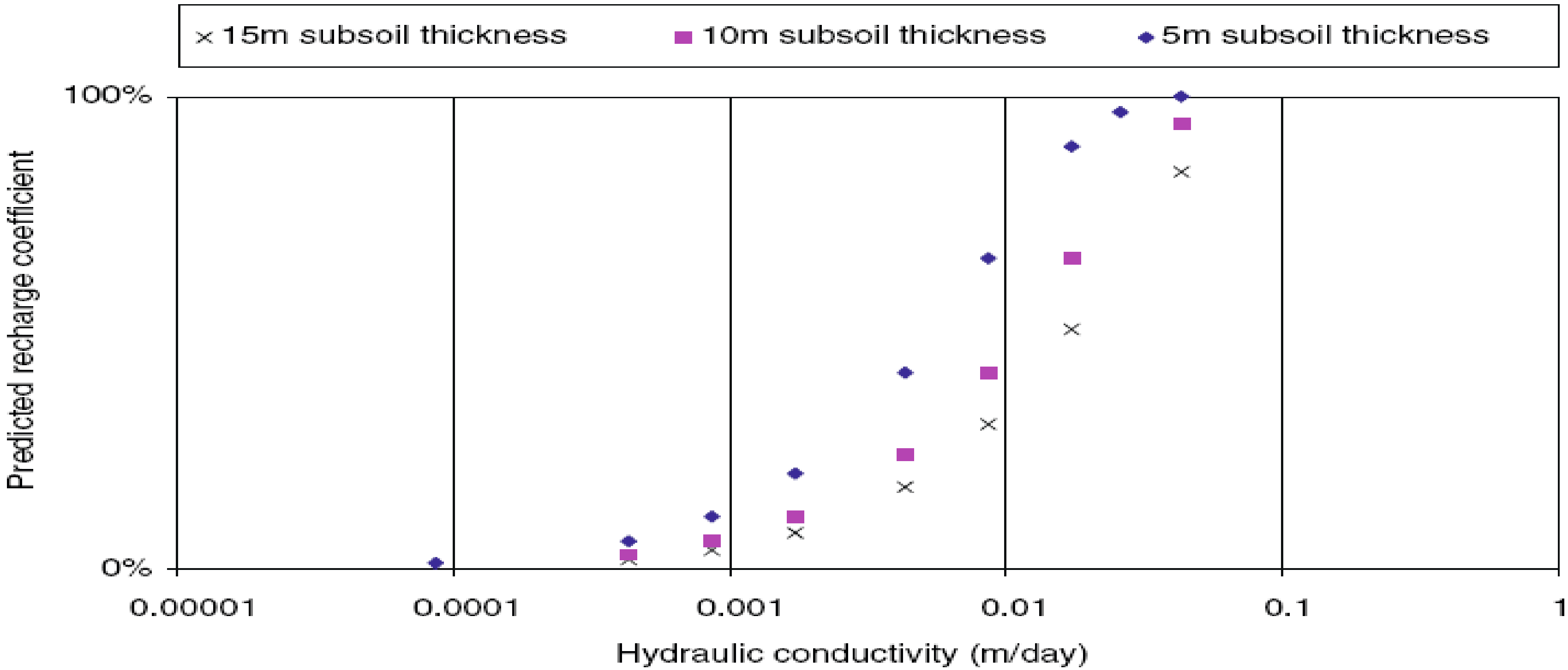


Fig. 9. Indicative structure and method of GIS-based tool for estimating recharge (adapted from Misstear *et al.* 2009*a*). RF, total rainfall; AE, actual evapotranspiration; ER, effective rainfall; PR, potential recharge; RC, recharge coefficient; RO, runoff.

(Hunter Williams et al. 2013)

Subsoil permeability is one of the main geological factors influencing direct (diffuse) recharge

(Fitzsimons & Misstear, 2006)



Generating recharge maps using GIS layers (Hunter Williams et al. 2013)

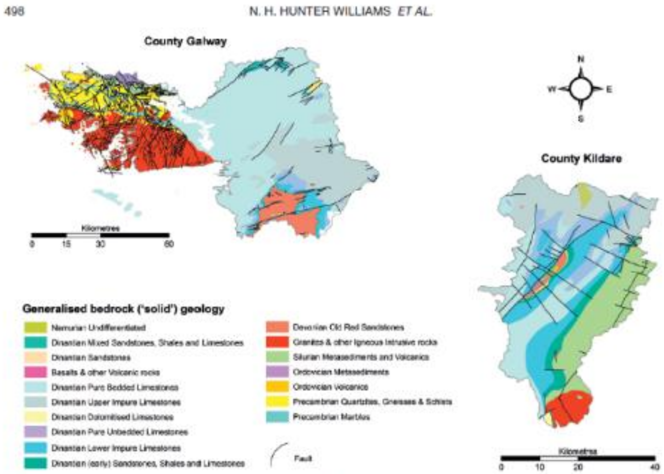


Fig. 2. Bedrock ('solid') geology underlying Counties Galway (left) and Kildare (right).

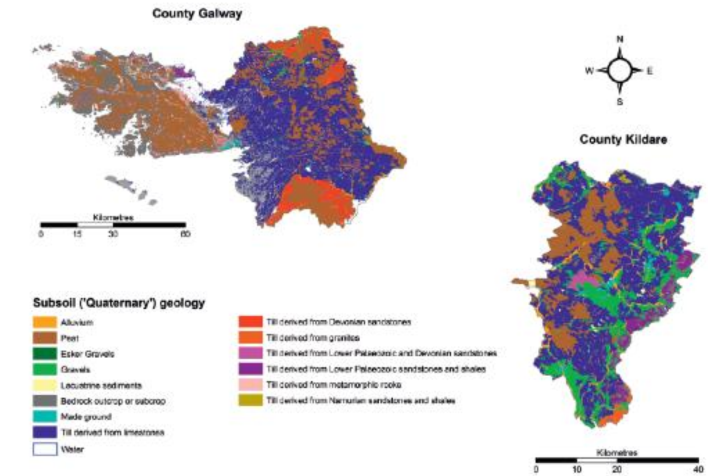


Fig. 3. Subsoil ('Quaternary') geology in Counties Galway (left) and Kildare (right).

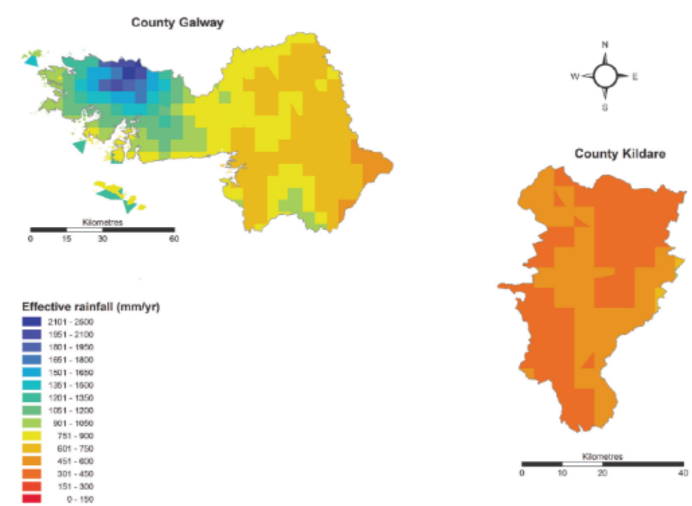


Fig. 4. Effective rainfall over Counties Galway (left) and Kildare (right).

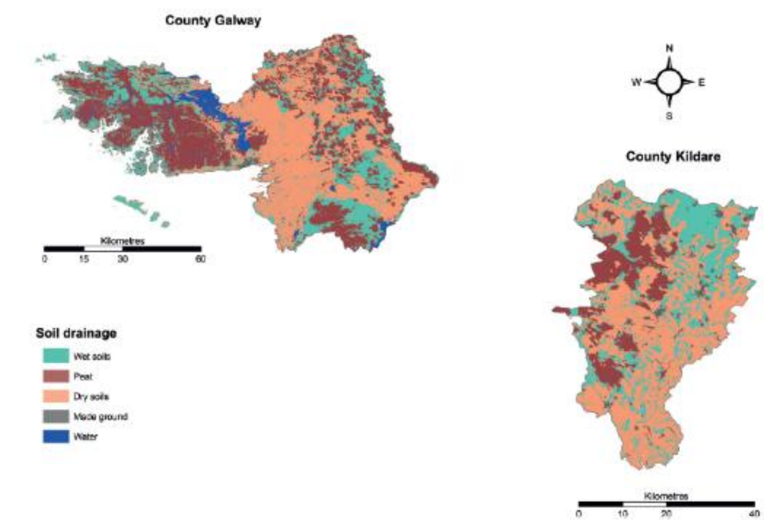


Fig. 5. Soil drainage in Counties Galway (left) and Kildare (right).

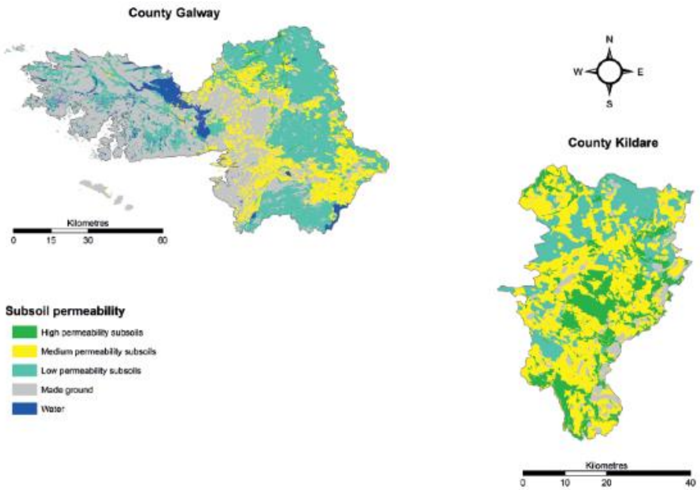


Fig. 6. Subsoil permeability in Counties Galway (left) and Kildare (right).

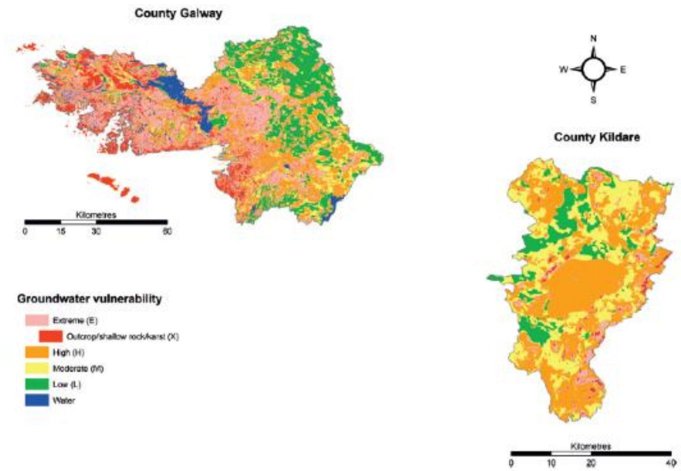


Fig. 7. Groundwater vulnerability in Counties Galway (left) and Kildare (right).

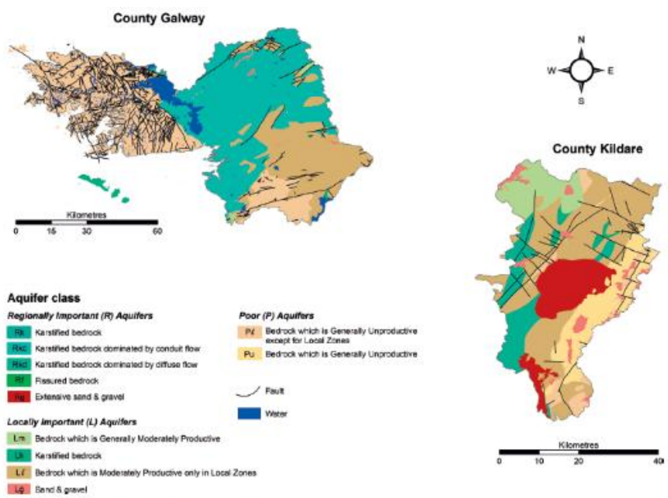


Fig. 8. Aquifers in Counties Galway (left) and Kildare (right).

(Hunter Williams et al. 2013)

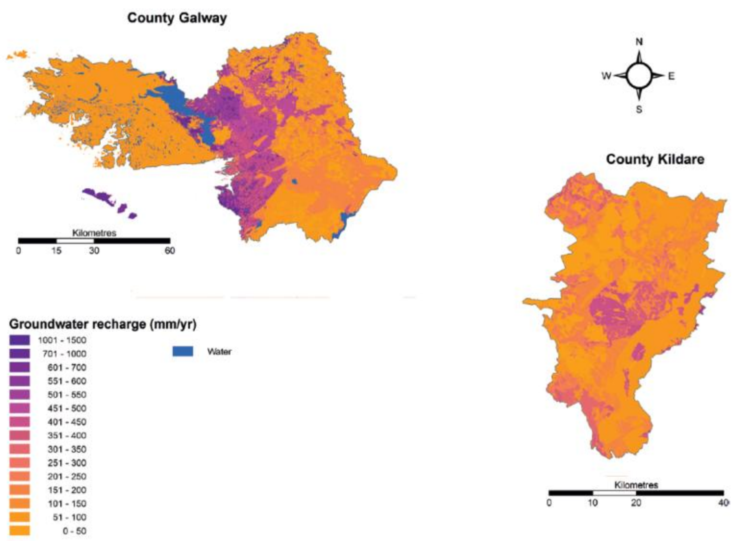


Fig. 11. Estimated average annual groundwater recharge in Counties Galway (left) and Kildare (right).

These maps show *direct (diffuse)* recharge

They provide *initial estimates* of recharge

Updates between 2011 and 2020 recharge maps

Dataset	2011 map	2020 map
Rainfall	30 year average annual rainfall 1971-2000. Data source Met Éireann.	MERA Daily rainfall in the period 1981-2010. Data source Met Éireann.
Actual Evapotranspiration	30 year average annual AE. Data source Met Éireann. One soil and reference crop type.	Daily AE in the period 1981-2010. Three soil drainage classes. One reference crop type. Data source ICHEC (2019). Modified by GSI for areas underlain by peat.
Effective Rainfall	Average Annual Effective Rainfall = $(\text{30 year average annual Rainfall} - \text{30 year average annual AE})$	Average Annual Effective Rainfall = $\sum_{1981}^{2000} \frac{(\text{daily rainfall} - \text{daily AE})}{30\ years}$
Grid cell size	5 km x 5 km	2.5 km
Soil drainage	Teagasc soils map 1:40,000 (Fealy, 2007), re-categorised by GSI to Wet, Dry, Peat, Made	Teagasc soils map 1:40,000 (Fealy, 2007), re-categorised by GSI to Wet, Dry, Peat, Made Teagasc Indicative Soil Drainage map 1:250,000 (Creamer *et al.*, 2016), re-categorised to well-drained, moderately-drained and poorly-drained soils Hybrid map created by mapping indicative soil drainage categories onto 1:40,000 soils map
Subsoil permeability and Groundwater vulnerability	GSI mapping available in 2011	GSI mapping available in 2020
Sand and gravel aquifers	GSI sand and gravel aquifer map (2008)	GSI sand and gravel aquifer map (2019)
Hydrogeological Scenarios	21 hydrogeological scenarios (excluding High-Low vulnerability areas)	24 hydrogeological scenarios (see table below. Better representation and improved recharge coefficients for peats; better representation of scree; additional scenarios for sand and gravel.

(Hunter Williams et al. 2021)

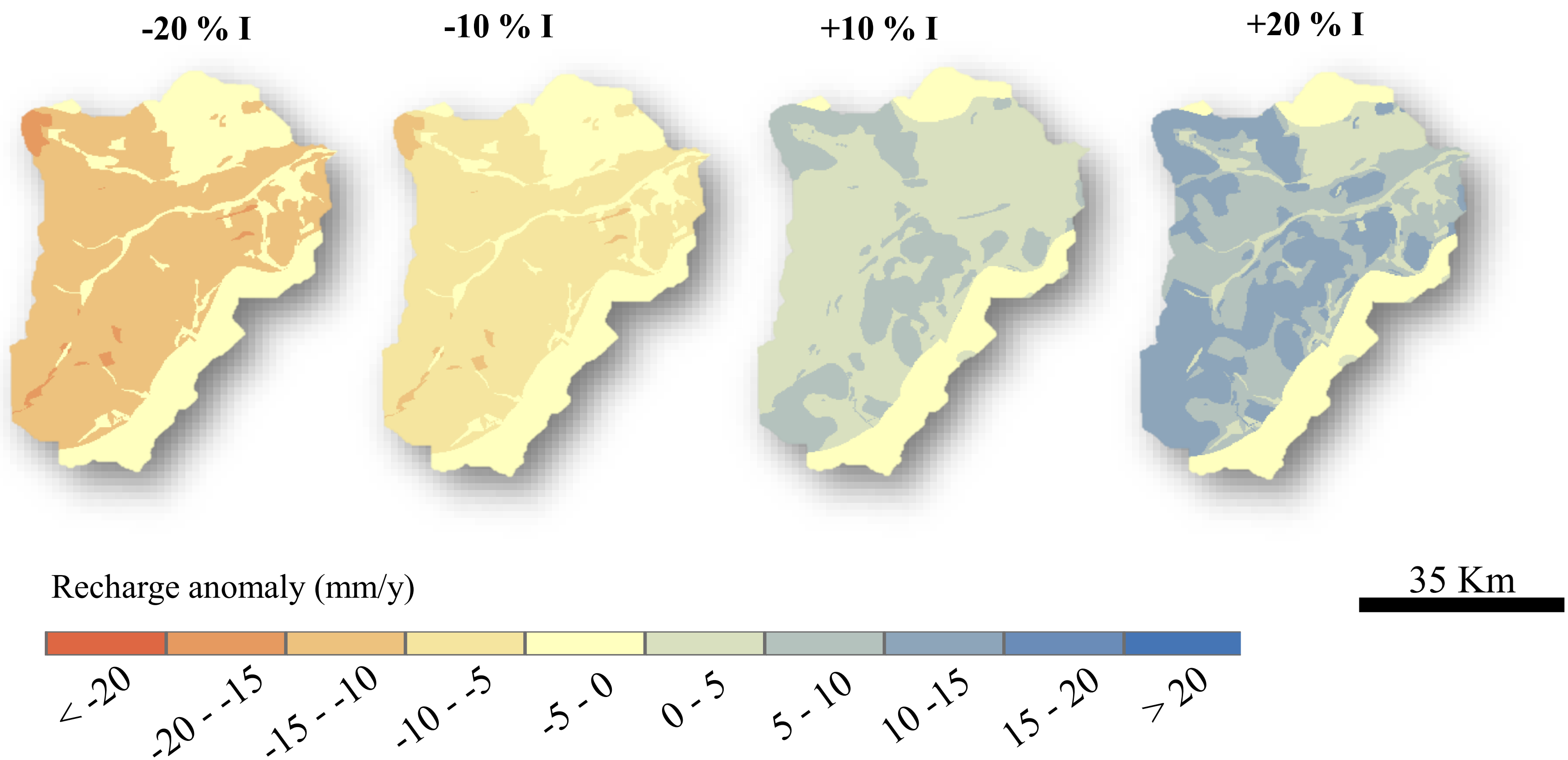
Updated Hydrogeological Scenarios

Hydrogeological scenario	Description	Recharge coefficients Lower	Mid	Upper
1.i	E Vul: Areas where rock is at ground surface or karst feature	30	80-90	100
1.ii	E Vul: Sand & gravel overlain by well-drained soil	50	80-90	100
1.iii	E Vul: Sand & gravel overlain by poorly-drained (gley) soil	15	35-50	70
1.iv	E Vul: Till overlain by well-drained soil	45	50-70	80
1.v	E Vul: Till overlain by poorly-drained (gley) soil	5	15-30	50
1.vi	E Vul: Sand & gravel aquifer where the water table is ≤ 3m below surface and overlain by well-drained soil	50	80-90	100
1.vii	E Vul: Sand & gravel aquifer where the water table is ≤ 3m below surface and overlain by poorly-drained soil or peat	1	3-5	10
1.viii	E Vul: Blanket peat and Cut peat	1	15-30	50
1.ix	E Vul: Fen peat	1	3-5	10
2.i	H Vul: Sand & gravel aquifer, overlain by well-drained soil	50	80-90	100
2.ii	H Vul: High permeability subsoil (sand & gravel) overlain by well-drained soil	50	80-90	100
2.iii	H Vul: High permeability subsoil (sand & gravel) overlain by poorly-drained soil or peat	15	35-50	70
2.iv	H Vul: Sand & gravel aquifer, overlain by poorly-drained soil or peat	15	35-50	70
2.v	H Vul: Moderate permeability subsoil overlain by well-drained soil	35	50-70	80
2.vi	H Vul: Moderate permeability subsoil overlain by poorly-drained (gley) soil	10	15-30	50
2.vii	H Vul: Low permeability subsoil	1	20-30	40
2.viii	H Vul: Peat	1	5-15	20
2.ix	H Vul: Fen peat	1	3-5	10
3.i	M Vul: Moderate permeability subsoil overlain by well-drained soil	35	50-70	80
3.ii	M Vul: Moderate permeability subsoil overlain by poorly-drained (gley) soil	10	15-30	50
3.iii	M Vul: Low permeability subsoil	1	10-20	30
3.iv	M Vul: Peat	1	3-5	10
4.i	L Vul: Low permeability subsoil	1	5-10	20
4.ii	L Vul: Basin peat	1	3-5	10

NB – made ground recharge coefficient is 20%. Maximum recharge capacities (recharge "caps") of 200 mm/yr and 100 mm/yr are assigned to LI, and PI, Pu aquifers respectively.

(Hunter Williams et al., 2021)

The recharge coefficient approach can be used to investigate the sensitivity of results to values of RCs and caps, and to future climate change scenarios. The example below shows impact of increasing or decreasing rainfall intensity (Nuenna catchment, Co Kilkenny)



Cantoni É et al. (2017) Climate change impacts on groundwater recharge to Irish fractured-bedrock aquifers. Proceedings of Irish National Hydrology Conference 2017, pp 3-12

The AQCLIMATE project is currently looking at the vulnerability of recharge to climate change. This EPA and GSI funded project is using Met Éireann’s TRANSLATE project dataset to investigate climate change scenarios and prepare recharge maps. The project leader is Patrick Morrissey (TCD) and partners include SETU Carlow and the ICHEC

See: (https://www.epa.ie/our-services/research/epa-funded-research/epa-funded-projects/research-data-table-dev/evaluating-the-vulnerability-of-aquifer-recharge-to-changing-climate-across-ireland.php)

Aquifer response analysis

- Can estimate recharge from water level fluctuations:

$$R = \left(\Delta h \times S_y\right) + Q_a + \left(Q_{out} - Q_{in}\right)$$

where R is the recharge, Δh the change in water table elevation, the specific yield, Q_a the groundwater abstraction during the period under consideration, and Q_{out} and Q_{in} are any other lateral subsurface outflows and inflows during the same period

- Major difficulty is getting a reliable value for S_y

Well hydrographs

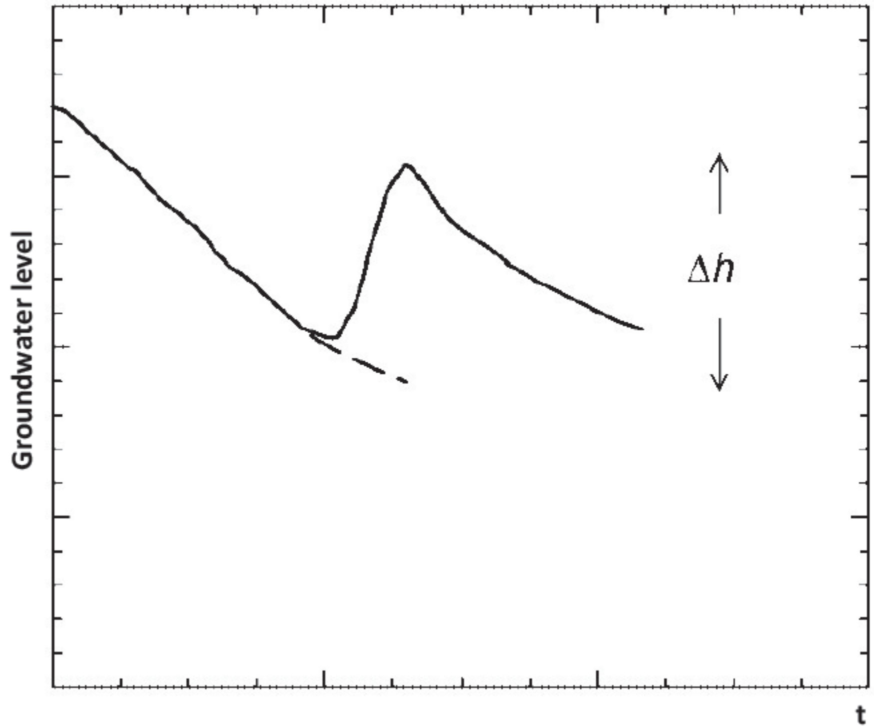
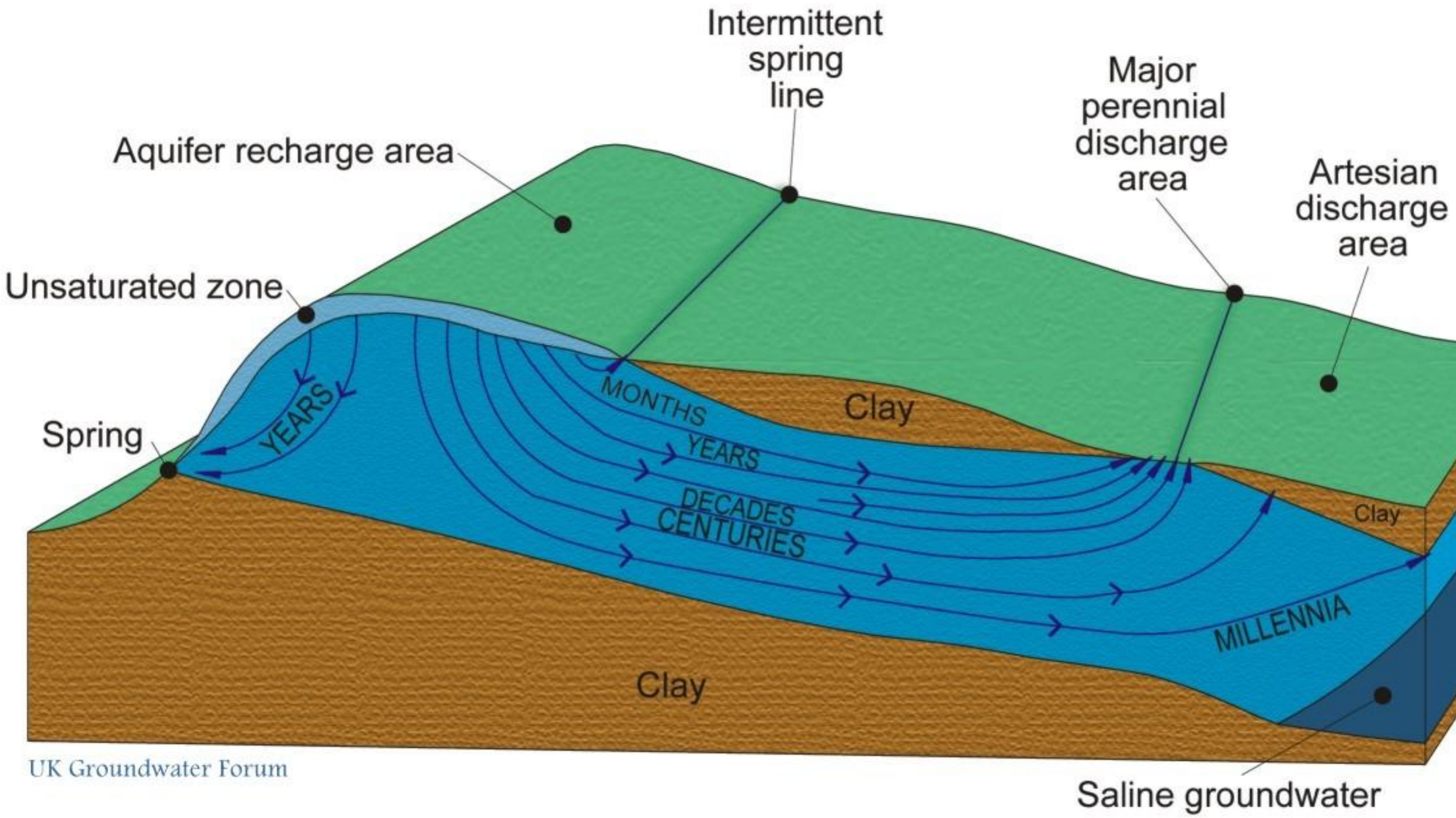


Fig. 9. The change in water table elevation for the specific yield calculations is defined as the difference between 'the peak of the rise and the low point of the extrapolated antecedent recession curve at time of the peak' (after Healy & Cook 2002).

Tedd *et al*. 2012:

Quarterly Journal of Engineering Geology and Hydrogeology, 45, 19–30
DOI: 10.1144/1470-9236/10-026.

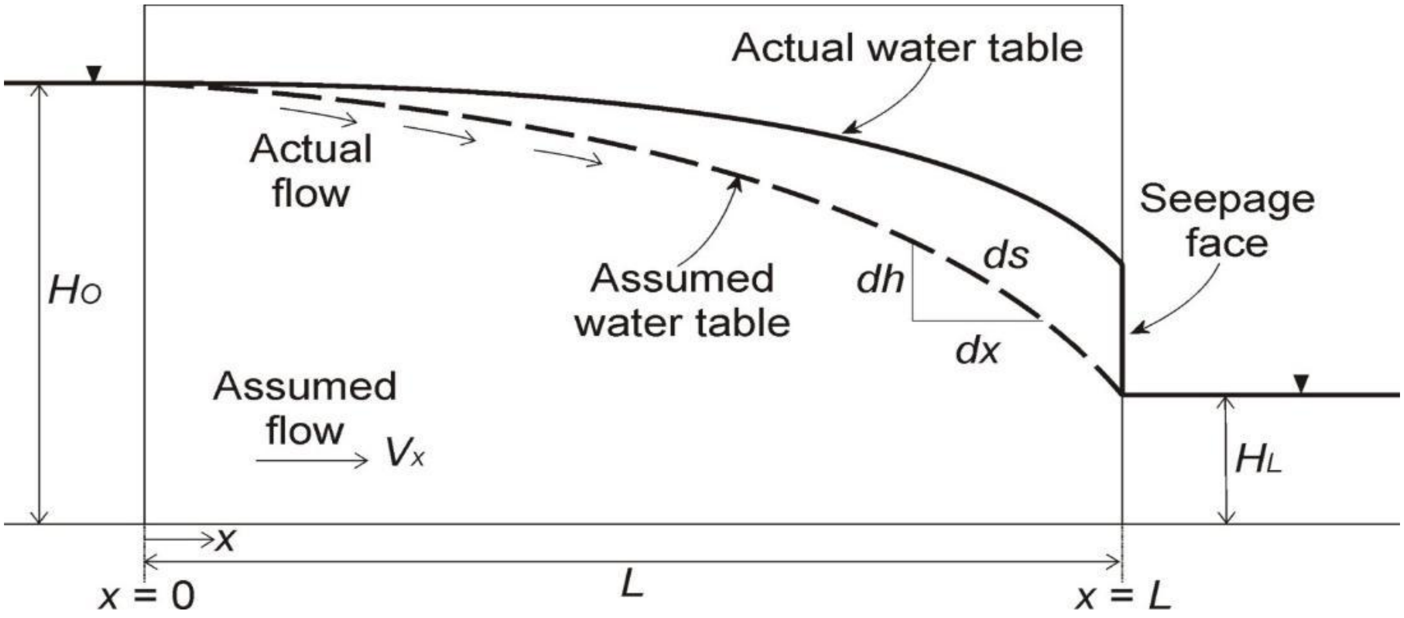
Aquifer throughput analysis



(UK Groundwater Forum image)

Aquifer throughput analysis

Can use Darcy or the Dupuit-Forchheimer equations

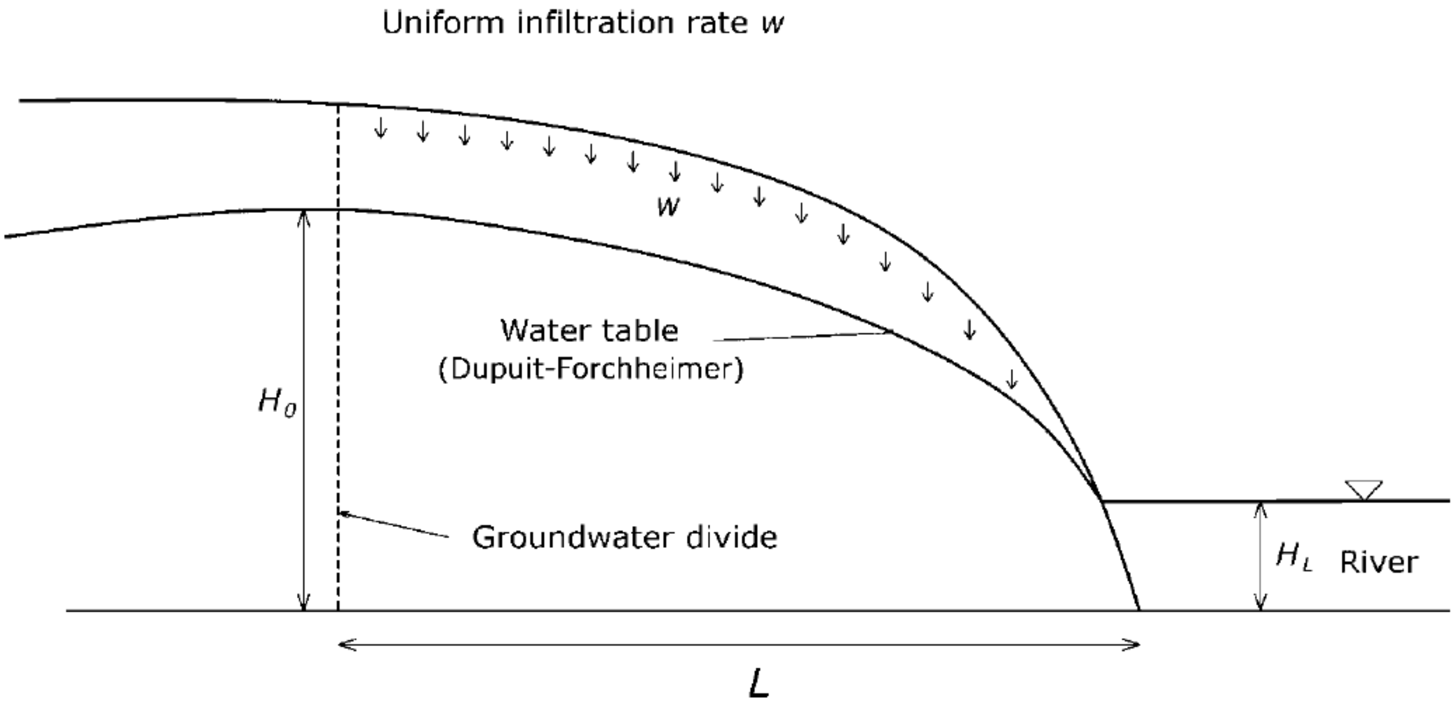


The flow per unit width through the vertical section of unconfined aquifer illustrated above is given by:

$$q = \frac{K}{2L}\left(H_0^{\,2} - H_L^{\,2}\right)$$

Application of D-F relationship to recharge estimation

(See Box 2.8 in Misstear et al. 2017)



$$w = \frac{K\left(H_0^2 - H_L^2\right)}{L^2}$$

Outflow estimation

Various methods for estimating the groundwater contributions to river flows including:

- hydrograph recession curve analysis
- digital filters
- minima turning point methods
- chemical end member mixing analysis
- models

Master recession curves

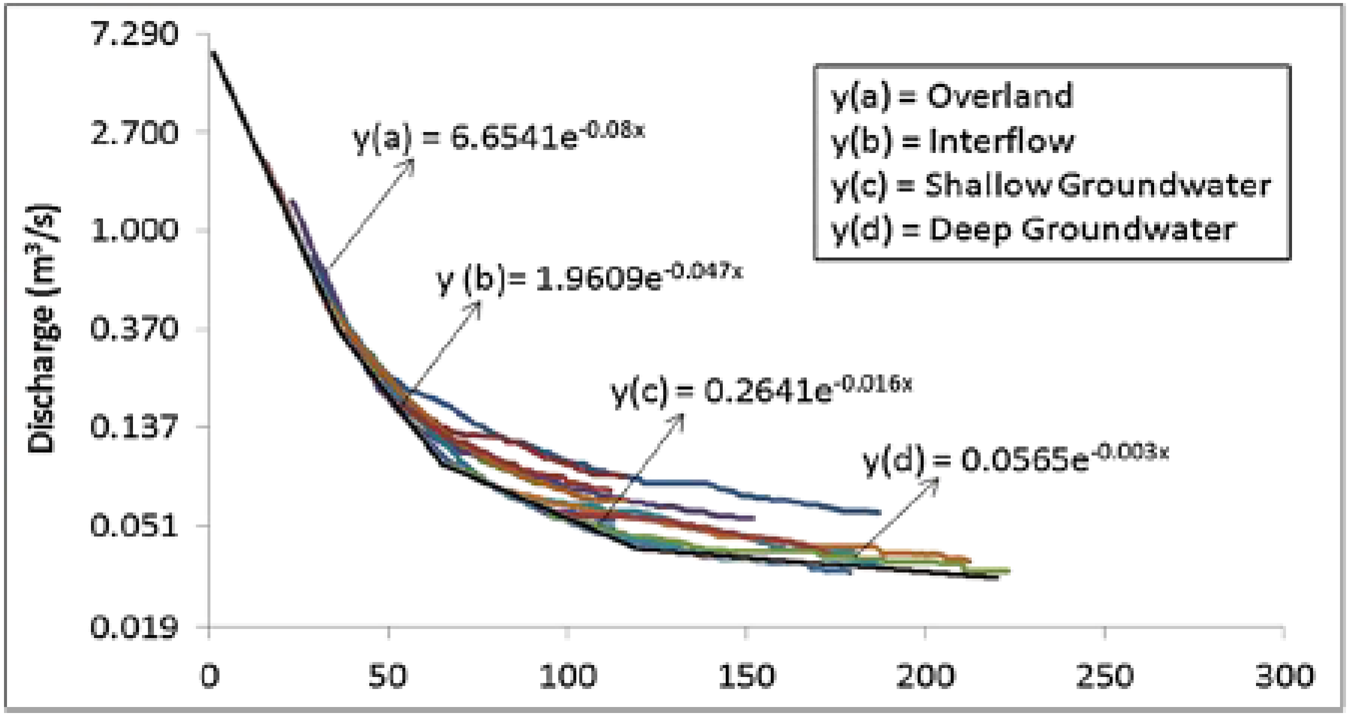


Figure 3. MRC analysis of the Glen Burn (Outlet) catchment

(O'Brien et al., in *Hydrological Processes* 2013)

Physical hydrograph separation methods

- River hydrographs can be successfully split into their main flow pathways using physical methods and a lumped hydrological model
- These physical hydrograph separations are based mainly on response times to rainfall
- Where different pathways have similar response times, then physical methods on their own are not sufficient and chemical methods can be used

Example of digital filter algorithm for separating out flow pathway components

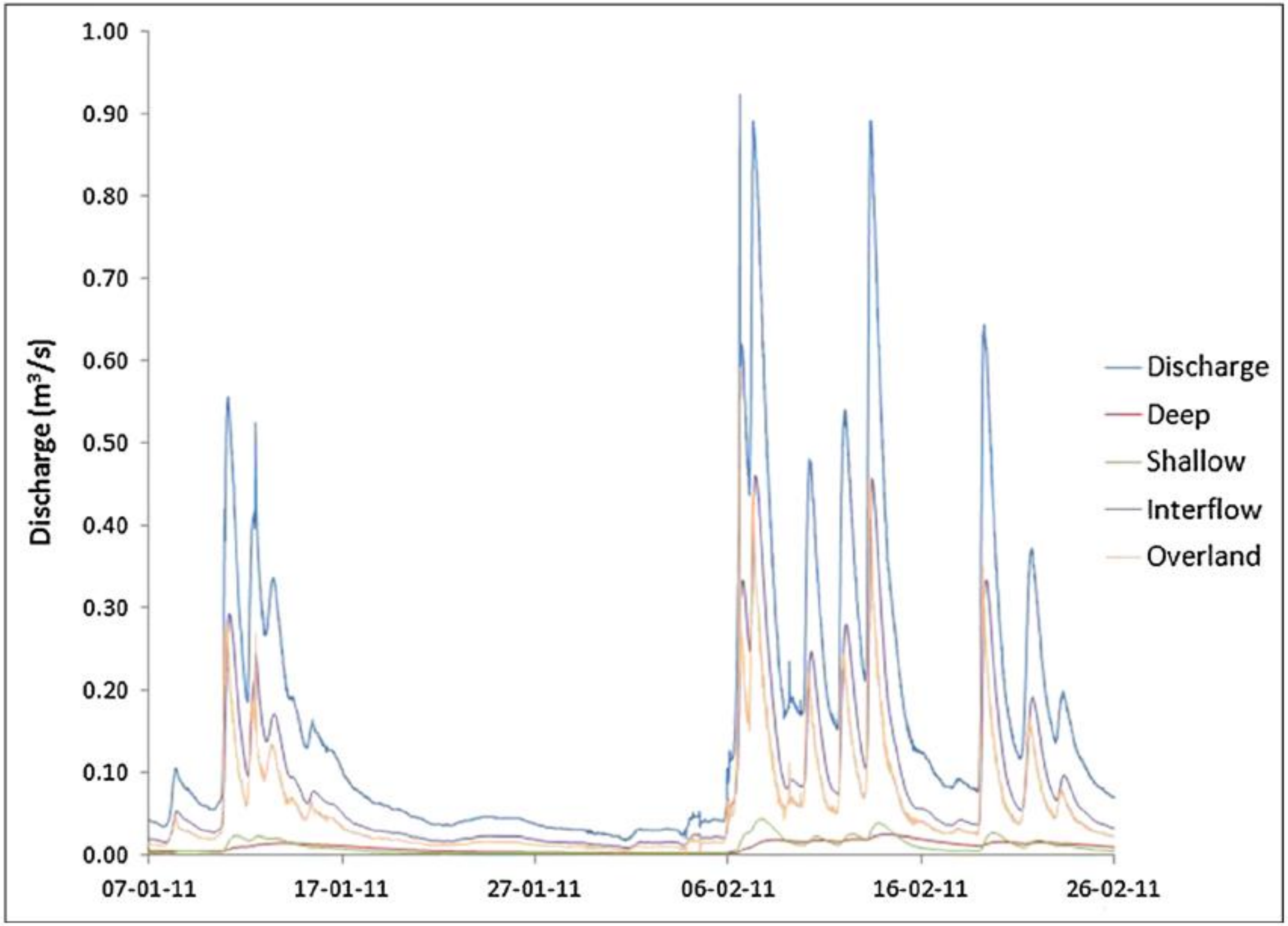


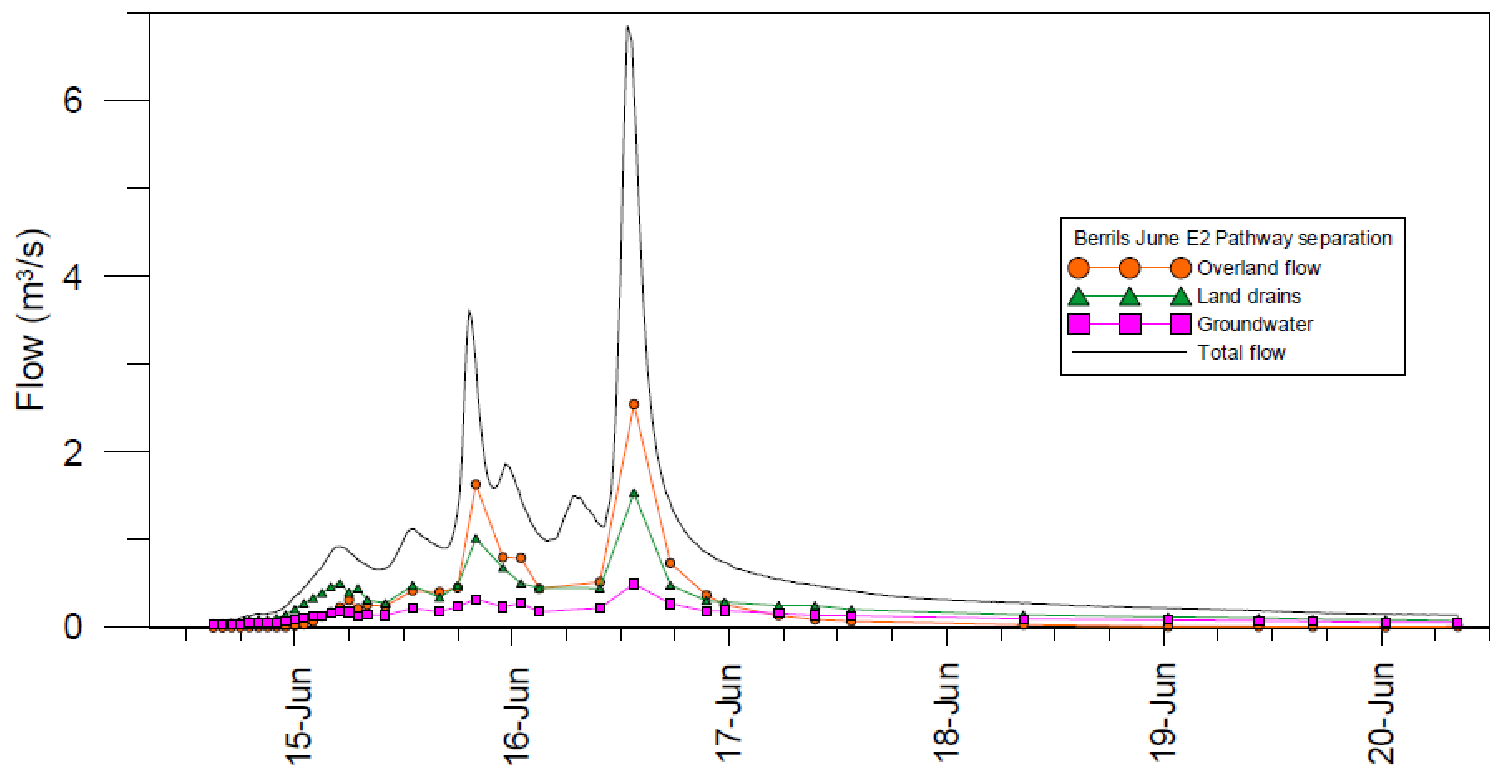
Figure 4. New algorithm applied to Glen Burn (Outlet)

(O'Brien et al. 2013)

Principles underlying chemical hydrograph separation

- Chemistry of rainfall evolves as water moves through the ground
- During an event, stream chemistry changes reflecting contributions from different pathways
- Pathways often have distinctive chemical signatures
- If you can isolate the pathway's signature, then you can calculate its contribution to total flow

Chemical pathway separation at the Mattock outlet (June 2012)



Archbold M, Deakin J, Packham I, Mockler E, Orr A, O'Brien R, Maher P, Thompson J, Cocchiglia L, Kelly-Quinn M, Desta M, Misstear BDR, Bruen M, Gill L, Ofterdinger U, Flynn R (2016) *Contaminant movement and attenuation along pathways from the land surface to aquatic receptors – Final report Volume 1, Field investigations and catchment conceptual models*. STRIVE Report, Environmental Protection Agency, Wexford, 180 pp

Chemical separations

G6 sub Nov 2011	G6 % Pathway contribution		
	Pre event	Peak flow	Total
OF	8	26	23
TZ	53	69	63
GW	39	5	14

G1 outlet Nov 2011	% Pathway contribution		
	Pre event	Peak flow	Total flow
OF	10	39	31
TZ	35	62	47
GW	54	0	22

G6 sub Dec 2012	% Pathway contribution		
	Low flow	Peak flow	Total
OF	5	88	22
TZ	64	8	57
GW	31	4	21

G1 outlet Dec 2012	% Pathway contribution		
	Low flow	Peak flow	Total flow
OF	2	88	28
TZ	62	9	50
GW	36	3	22

NAM model

G6 Nov 2011	% Pathway contribution (NAM)		
	Low flow	Peak flow	Total flow
OF	0	95	58
IF	70	3	27
Sh GW	15	1	9
D GW	15	1	6

G1 Nov 2011	% Pathway contribution (NAM)		
	Low flow	Peak flow	Total flow
OF	0	93	61
IF	67	4	25
Sh GW	18	1	9
D GW	14	1	5

G6 Dec 2012	% Pathway contribution (NAM)		
	Low flow	Peak flow	Total flow
OF	0	84	34
IF	78	13	48
Sh GW	11	2	10
D GW	11	2	8

G1 Dec 2012	% Pathway contribution (NAM)		
	Low flow	Peak flow	Total flow
OF	0	87	42
IF	76	10	41
Sh GW	13	2	10
D GW	11	1	7

Figure 2.12. Comparison of the chemical (left) and equivalent NAM-modelled (right) pathway separations for the November 2011 and December 2012 events in the Gortinlieve catchment. D, deep; GW, groundwater; IF, interflow; OF, overflow; Sh, shallow; TZ, transition zone.

(Archbold *et al.*, 2016)

Catchment water balances and modelling

A simple water balance relationship for an aquifer:

$$w + Q_i = Q_o + Q_{dis} + Q_{abs} \pm \Delta\sigma_g$$

where w = recharge to the aquifer, Q_i = any other lateral or vertical inflows from adjacent aquifer units, Q_{abs} = groundwater abstraction, Q_{dis} = discharge of groundwater to the surface as springs or river baseflow, Q_o = any other outflows to adjacent aquifer units (or direct evaporation from water table) and $\Delta\sigma_g$ the change in groundwater stored in the aquifer.

Models

Various mathematical models can be used to estimate recharge, including:

- Lumped or distributed models
- Unsaturated zone models
- Groundwater flow models
- Catchment models

Whatever modelling approach is used, we need to start off with a proper conceptual model

Recent pan-European modelling study (Seidenfaden et al., 2023)

Table 1

Overview of components included and data inputs and outputs from the three models. x – Included in the model; a - please see footnote.

TYPE	DATA	Metran	AquiMod	GARDÉNIA
INPUT DATA	Precipitation	x	x	x
	Temperature	* *		x
	Potential evapotranspiration	x	x	x
	Groundwater abstraction	x	x	x
	Groundwater levels	x	x	x
	Stream Discharge			x
SURFACE OUTPUT DATA	Surface runoff		x	x
	Actual evapotranspiration		x	x
	Snowmelt			x
	Stream discharge		*	x
SUB-SURFACE OUTPUT DATA	Groundwater levels	x	x	x
	Potential recharge			
	Recharge	x	x	x
	Inter-aquifer leakage		x	

* * Metran can be used with temperature instead of evapotranspiration, but this requires special adaptation in the calculation of recharge.
[a] AquiMod model produces aquifer discharges. Under certain conceptualisation, these discharges can be considered as stream discharges.

The models produced different recharge estimates. The results were improved when local information on the system was added (including water balance)

Curragh aquifer case study: summary of effective rainfall and recharge estimations (Misstear et al. 2009)

Table 7 Summary of results for the Curragh aquifer

Approach	Method/parameter	Determinant	Values
Soil moisture balance	FAO Penman-Monteith	Effective rainfall	321–366 mm/year
Soil moisture balance	Penman-Grindley	Effective rainfall	334 mm/year
Hydrograph analysis	S_y=0.13	Recharge coefficient	40–80%
Hydrograph analysis	S_y=0.19	Recharge coefficient	70–100%
Catchment water balance	2002–2005 canal discharge data	Recharge	284 mm/year
Catchment water balance	2002–2005 canal discharge data	Recharge coefficient	81–85%

Hydrogeology Journal DOI 10.1007/s10040-008-0376-0

Take home messages

- Recharge is one of the most difficult components of the hydrological cycle to evaluate
- Important to distinguish between methods that give estimates of *potential* recharge and methods that indicate *actual* recharge
- Different approaches often give different answers, so best to use a combination of methods when estimating recharge

Selected references on groundwater recharge

COOK P, BRUNNER P (2025) *Quantification of Groundwater Recharge*. The Groundwater Project (this book is available as a free download)

FITZSIMONS V, MISSTEAR BD (2006) Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. *Hydrogeology Journal* 14: 548-561

HEALY R (2010) *Estimating groundwater recharge*. Cambridge Univ Press

HUNTER WILLIAMS NH, MISSTEAR BDR, DALY D, LEE M (2013) Development of a national groundwater recharge map for the Republic of Ireland. *Quarterly Journal of Engineering Geology and Hydrogeology* 46: 493-506

HUNTER WILLIAMS NH, CAREY S, WERNER C, NOLAN P (2021) Updated National Groundwater Recharge Map. *Irish Groundwater Newsletter* 59: 31-34

LERNER DN, ISSAR AS, SIMMERS I (1990) *Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge*. International Association of Hydrogeologists International Contributions to Hydrogeology Volume 8, Heise

MISSTEAR BD, BANKS D, CLARK L (2017) *Water wells and boreholes,* 2nd edition. Wiley (see Section 2.6)

MISSTEAR BD, BROWN L, JOHNSTON P (2009) Estimation of groundwater recharge in a major sand and gravel aquifer in Ireland using multiple approaches. *Hydrogeology Journal* 17: 693-706

O'BRIEN RJ, MISSTEAR BD, GILL LW, JOHNSTON P, FLYNN R (2013) Quantifying flows along hydrological pathways by applying a new filtering algorithm in conjunction with master recession curve analysis. *Hydrological Processes* 28: 6211-6221

SCANLON BR, COOK PG (2002) Theme issue: Groundwater recharge, *Hydrogeology Journal* 10: 1-237

SEIDENFADEN et al (2023) Evaluating recharge estimates based on groundwater head from different lumped models in Europe. *Journal of Hydrology: Regional Studies* 47: 101399