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The role of wetlands in the hydrological cycle

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Abstract

It is widely accepted that wetlands have a significant influence on the hydrological cycle. Wetlands have therefore become important elements in water management policy at national, regional and international level. There are many examples where wetlands reduce floods, recharge groundwater or augment low flows. Less recognised are the many examples where wetlands increase floods, act as a barrier to recharge, or reduce low flows. This paper presents a database of 439 published statements on the water quantity functions of wetlands from 169 studies worldwide. This establishes a benchmark of the aggregated knowledge of wetland influences upon downstream river flows and groundwater aquifers. Emphasis is placed on hydrological functions relating to gross water balance, groundwater recharge, base flow and low flows, flood response and river flow variability. The functional statements are structured according to wetland hydrological type and the manner in which functional conclusions have been drawn. A synthesis of functional statements establishes the balance of scientific evidence for particular hydrological measures. The evidence reveals strong concurrence for some hydrological measures for certain wetland types. For other hydrological measures, there is diversity of functions for apparently similar wetlands. The balance of scientific evidence that emerges gives only limited support to the generalised model of flood control, recharge promotion and flow maintenance by wetlands portrayed throughout the 1990s as one component of the basis for wetland policy formulation. That support is confined largely to floodplain wetlands, while many other wetland types perform alternate functions — partly or fully. This paper provides the first step towards a more scientifically defensible functional assessment system.

**Keywords:** wetlands, hydrological functions, flood reduction, groundwater recharge, low flows, evaporation

Introduction

Open any book on wetland conservation and it will encourage the management of wetlands partly because of their role in the water cycle. Wetlands are said to perform “hydrological functions”; to “act like a sponge”, soaking-up water during wet periods and releasing it during dry periods (e.g. Bucher et al., 1993). As Malthby (1991) reports “…the case for wetland conservation is made in terms of ecosystem functioning, which result in a wide range of values including groundwater recharge and discharge, flood flow alteration, sediment stabilization, water quality ….”. Since wetlands cover around 6% of the land surface of the earth (OECD, 1996) and many exist in the upstream parts of river catchments, the total downstream area over which a hydrological influence may be exerted is substantial. Yet the hydrological processes and behaviour of wetland ecosystems has certainly lacked the scientific integration received by other land surface systems, such as forests.

Kusler and Riexinger (1985) reported that “the science base and efforts to assimilate existing studies are still inadequate with regard to some functions, particularly hydrology”.

The basic references on the hydrological functions of wetlands are summaries of studies collated in the USA in the 1980s (Adamu and Stockwell, 1983; Bardecki, 1984; Carter, 1986). These summaries have been used by organisations, such as IUCN-The World Conservation Union (Dugan, 1990), Wetlands International (Davis and Claridge, 1993) and the Ramsar Convention on Wetlands of International Importance (Davis, 1993). They have influenced international wetland policy (OECD, 1996) and its uptake at the national (e.g. Zimbabwe and Uganda), and continental levels e.g. Europe (CEC, 1995) and Asia (Howe et al., 1992).

Recent emphasis at the Second World Water Forum in The Hague 2000 and the World Summit on Sustainable Development 2002 in Johannesburg was placed on the need
to ensure the integrity of ecosystems as part of integrated water resources management. Also receiving high prominence was the use of water to meet basic human needs and economic development. Thus, it is essential to re-examine, periodically, the conclusions of scientific studies on wetland functions. This ensures that policy at all levels is underpinned by a consensus of sound scientific opinion.

The scientific literature contains a range of studies that describe the water quantity functions of individual or groups of wetlands. They represent a substantial accumulation of hydrological knowledge. The majority of these papers supports the notion that wetlands have a significant influence on the hydrological cycle. However, many recognise that “it is difficult to make definitive statements regarding the role of various types of wetlands in runoff production or storm water detention” (Carter, 1986). Furthermore, some studies have produced evidence that contradicts previous widely accepted knowledge. For example, the classic hydrological studies of Hewlett and Hibbert (1967) identified headwater wetlands along river margins as flood generating areas. Burt (1995) concluded that “... most wetlands make very poor aquifers; ... accordingly, they yield little base flow, but in contrast, generate large quantities of flood runoff. Far from regulating river flow, wetlands usually provide a very flashy runoff regime”.

This paper has three objectives: first, to present an ordered database of published papers on hydrological functions of wetlands; second, to provide a collation of scientific evidence among hydrological measures and wetland type; third, to stimulate debate and further research. The focus of this paper is limited to water quantity functions, including impacts on water resource availability, groundwater replenishment and flood control. It does not consider other aspects of wetlands, such as water quality or biodiversity, which are part of a wider case for wetland conservation.

Creating a literature-based review of water quantity functions

With the objective of creating a comprehensive and consistent database of past studies, a literature review of water quantity functions was undertaken by keyword searches on the major databases of abstracts, and by tracking citations to earlier and related studies. Consequently, the database is drawn from 169 publications that report the results of scientific study that quantify hydrological functions of wetlands. Papers that report other authors’ findings or give only qualitative descriptions of wetland process are not included.

Certain guidelines were followed, namely that:

- the review is restricted to freshwater wetlands, excluding lakes;
- conclusions of wetland function must be supported by hydrological data and not based on the original author’s opinion alone;
- double-accounting is avoided, whereby repetition of conclusions for an individual wetland in successive publications is not duplicated;
- unsubstantiated generic statements, such as wetlands reduce flooding, are not included.

Consistency is ensured by extracting common elements from the diverse sources. Important information is maintained in the detail of the particular hydrological function, wetland type and the manner of conclusion. The approach adopted was to complete the following general statement (where bracketed and underlined phrases relate to elements in Annex 1) for each study:

“(Author(s)) undertook a study in a given location (country, or US State/Canadian Province or Territories) of a particular hydrological type of wetland (wetland type), also referred to by a more general or locally-specific wetland term (local term). Based on results from a particular type of study (categorisation of wetland study) and drawing inferences in a particular manner (basis of inference), the authors conclude (page number) that the wetland performs a particular function with respect to a specific hydrological measure (hydrological measure), as can be summarised by a functional statement (summary functional statement) and a summary function (summary of wetland water quantity function)”.

There are, therefore, ten elements extracted from each publication, each entered into the database. Explanation of each of these elements is expanded upon below. Because the format of the review is tabular, abbreviated codes are adopted for some elements for purposes of brevity.

Author(s): Citation to original source.

Country, or US State/Canadian Province or Territories: Location of wetland study.

Wetland type: For the purpose of this study, wetlands are categorised into five types according to three broad hydrological features (Table 1), based, with modification, upon the scheme proposed by Novitski (1978) for Wisconsin wetlands and subsequently applied by Adamus and Stockwell (1983). The three hydrological features are general catchment location, connectivity with the groundwater system and connectivity with the downstream channel network. General catchment location distinguishes
between headwater and floodplain; the distinction is that headwater wetlands are not fed by significant stream sources. Further subdivision applies only to headwater types. The connectivity with the groundwater system distinguishes ‘groundwater’ types that are in hydraulic connectivity with the groundwater system for all, or part of, the time, from ‘surface water’ types, which are not. Connectivity with the downstream channel network distinguishes ‘slope’ types, which are characterised by an outlet to the downstream river system, from ‘depression’ types, which are not. This categorisation deviates from that of Novitski and Adamus and Stockwell by including a floodplain type and in the ‘surface–slope’ type which, in that scheme, categorises lakeshore wetlands. Therefore, the two schemes are similar but are not directly comparable. An unspecified category is added, and applied where the hydrological context of the wetland cannot be discerned.

**Local term:** Many local terms are applied to wetlands, including such general anglicised terms as ‘marsh’, ‘swamp’, ‘bog’ etc, and regionally specific terms such as dambo, pakihi, pocosin. There is no known means of providing a direct association between local terms and hydrological type in a fully inclusive manner.

**Categorisation of wetland study:** Wetland studies have adopted a number of experimental frameworks, ranging from intensive long-term monitoring of the water balance of wetland and non-wetland at the most complex extreme, to analyses based on single flood event hydrographs. Table 2

### Table 1. Categorisation of wetland type by hydrological features

| Type            | Wetland type   | Code | Features                                                                 |
|-----------------|----------------|------|--------------------------------------------------------------------------|
| Headwater       | Surface water depression | SW/D | No hydraulic connectivity with groundwater. Outlet has no direct connectivity with river system |
|                 | Surface water slope         | SW/S | No hydraulic connectivity with groundwater. Outlet has direct connectivity with river system |
|                 | Groundwater depression      | GW/D | Hydraulic connectivity (permanent or periodic) with groundwater. Outlet has no direct connectivity with river system |
|                 | Groundwater slope           | GW/S | Hydraulic connectivity (permanent or periodic) with groundwater. Outlet has direct hydraulic connectivity with river system |
| Floodplain      | Floodplain                 | FP   | Inputs are dominantly upstream river flows                                |
| General         | Wetland type, or one element of the type, cannot be specified |

### Table 2. Categorisation of methodological approach to wetland studies

| Category of wetland study | Code | Code |
|---------------------------|------|------|
| Conceptual catchment model| CCM  | Calibration and application of a conceptual catchment model |
| Water balance             | WB   | Quantification of the terms of the catchment and/or wetland water balance |
| Long-term hydrograph      | LTH  | Analysis of the characteristics of long time series of river flows |
| Single-event hydrograph   | SEH  | Analysis of the characteristics of a single river flow event |
| Trend analysis in time series | TS  | Analysis of trends in hydrological time series (associated with detecting the impacts of drainage) |
| Component process         | COMP | Investigation of an individual water balance component or hydrological process. (See Table 4 for definitions of ‘a’)
| Chemical balance          | CHEM | Quantification of a chemical process or chemical balance |

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presents categories of methodological approach with abbreviated codes for brevity in the tabular review.

**Basis of inference:** Many studies draw conclusions of the kind that, for example, wetlands reduce floods or augment dry season river flows. This kind of conclusion, when taken out of context, leaves unanswered the basis for that conclusion, notably that the wetland reduces (or increases) river flows — compared with what? Table 3 presents a set of the comparative scenarios used amongst the various

| Code | Baseline for inference | Methodology | Limitations |
|------|------------------------|-------------|-------------|
| Without | Comparison of the same basin, with or without a wetland | This approach is restricted to catchment model simulations, in which the model is calibrated in either the “with” or “without” wetland case, as occurs in the modelled catchment. Model runs with the wetland case reversed generate simulated hydrological outputs. Differences between observed and simulated outputs are attributed to the presence of the wetland. | One case is simulated only. Stability of model parameters. Response of wetland replacement zone. |
| Drained | Comparison of the same wetland basin before and after drainage; or neighbouring drained and undrained wetlands | Hydrological outputs from a wetland are observed prior to drainage. The wetland is drained, and outputs are observed after drainage. Differences in the pre- and post- drainage outputs are attributed to the wetland. alternately, outputs from two adjacent catchments, each with wetlands, are observed. One of the catchments is drained, and differences between the outputs between the two catchments are attributed to the presence of the wetland. | Response of replacement land-use in drained wetland. Initial short-term responses to drainage may differ from long-term responses. |
| Pair | Comparison of paired basins, one with wetland the other without | Hydrological outputs are observed from two catchments, similar in all respects except that one that one catchment contains a wetland while the second does not. Differences between the outputs are attributed to the presence of the wetland. | If two catchments are otherwise identical, why does only one have a wetland? |
| Multiple | Comparison of several basins with varying proportions of wetland | Hydrological outputs are observed from several catchments, each containing different proportions of wetland. Differences between the outputs are attributed to greater or lesser presence of wetland. | Variability in non-wetland characteristics amongst several catchments |
| In-out | Comparison of inflows and outflows of a wetland system | Hydrological inputs and outputs associated with a single wetland are measured. Differences between inputs and outputs are attributed to the presence of the wetland. | |
| Same | Comparison of wetland hydrological response with response elsewhere in the same basin | Hydrological outputs from a single wetland are measured as well as outputs from other non-wetland portions of the same catchment. Differences between the outputs are attributed to the wetland. | |
| Comp | Conclusions relating to individual components of the wetland through the development of an understanding of a component process | Individual component processes are observed and understood within a single wetland. The understanding of the processes is the basis for inferring the influence of that process on the hydrological output. (Substituting for T = topography, V = vegetation, S = Soil, WC = water content, GW = groundwater, ET = evaporation) | Extrapolation of a single process in isolation. Processes may not be homogeneous across the entire wetland. |
publications as the basis for inferring wetland function. Each basis has some limitations, and these are summarised. Again, abbreviated codes are set out.

Page number: Page number in the original publication on which the conclusion is drawn.

Hydrological measure: There are many different measures in hydrology to describe and define aspects of the flow regime. While non-hydrologists might refer generically to floods, the hydrologist would be concerned with measures such as the magnitude of the peak flow during the flood event, the volume of runoff contained in the event, and the time-to-peak. Published studies in wetland hydrology are not consistent in their attention to different measures; it is possible to find one study analysing the return period of flood peaks extracted from a 20 or 30 year flow record, and another analysing the flood volume of a single event, with both drawing conclusions on wetland influences on floods.

Table 4 presents and defines different hydrological measures within five broad groupings of hydrological response, namely; gross water balance, groundwater recharge, base flow and low flows, flood response and river flow variability, including some seasonal variations.

Summary of wetland water quantity function: Conclusions regarding water quantity functions extracted directly, or in paraphrased form, from the original text are presented.

Summary functional statement for hydrological measure: Functional statements of the form ‘wetlands increase low flows’ are expressed as the sign of the wetland influence upon the hydrological measure; thus ‘+’ indicates an increasing influence upon the hydrological measure, ‘-’ indicates a reducing influence and ‘.’ represents a neutral influence (i.e. no significant influence exists or can be detected). In the case of groundwater recharge and groundwater discharge sites, there is interest in the conservation-based literature whether either of these functions is, or is not, present in a wetland. Therefore, ‘=’ indicates that this function is present and ‘x’ indicates that it is not.

Global data base of wetland water quantity functions

The first objective of this paper is to redress the deficiency in availability of hydrological information on wetland functions by providing an accessible and consistent database of past studies. Annex 1 presents the product of the application of the global review. The database is composed of 169 different published studies with 440 functional statements, representing the fullest sample of studies that could be traced, conforming to the principles adopted. It would not be claimed that the sample is exhaustive, but it is considered to be comprehensive.

Table 5(a to e) collates the number of functional statements for each wetland type for the five principal groups of water quantity measures. For example, interpreting Table 5a for floodplain-type wetlands, two studies conclude that an example of this wetland type increases mean annual flow, two studies concludes that no significant influence can be detected and eight studies conclude that examples of this wetland type reduce mean annual flow. Total numbers of functional statements are presented across all hydrological measures and all wetland types.

Analysis of the “balance of scientific evidence” draws on comparison of the number of papers that conclude a particular function. This is seen to be an important step and a precursor to more detailed exploration of the evidence for particular measures for specific wetland types. The results cannot yet be considered to reflect a “balance of scientific opinion”, because there has been no inter-comparison amongst the different studies.

There are some cautionary perspectives and some limitations on the comparison that must be stated.

1. The number of papers reporting a particular influence on the water cycle does not necessarily indicate the total picture. Some hydrological functions have been studied more than others.

2. The number of functional statements cannot be interpreted as the number of wetlands performing a function; for example, a functional statement based on multiple catchments commonly involves a large number of individual wetlands.

3. There is no certainty that the 169 publications represent all past studies of wetlands Although not exhaustive, the sampling method has been applied independently of any initial bias associated with policy interests. However, it cannot be discounted that there is potential bias in the wetlands that were selected for study by the original authors.

4. The distribution of wetland types within the sample of reviewed studies does not represent the distribution of wetland types worldwide; this is particularly true given
Table 4. Hydrological measures and their definition

| CODE   | Hydrological measure                                      | Definition                                                                                                                                 |
|--------|-----------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| GROSS WATER BALANCE                      |                                                            |                                                                                                                                        |
| MAF    | Mean annual flow                                          | Volume (or rate) of river flow during a year (on average)                                                                              |
| MAAE   | Mean annual actual evaporation                           | Volume (or rate) of evaporation during a year (on average)                                                                             |
| WPF    | Wet period flow                                           | Volume (or rate) of river flow during, or in response to, periods of rainfall                                                         |
| WPAE   | Wet period actual evaporation                             | Volume (or rate) of evaporation during, or in response to, periods of rainfall                                                         |
| DPAE   | Dry period actual evaporation                             | Volume (or rate) of evaporation during periods without rainfall                                                                       |
| Dry period flow                           |                                                            | See ‘DPFV’ - Dry period flow volume                                                                                                   |
| GROUNDWATER RECHARGE                      |                                                            |                                                                                                                                        |
| AGR    | Annual groundwater recharge system during a year          | Volume of water moving vertically from the wetland into the underlying groundwater                                                     |
| WPGR   | Wet period groundwater recharge system during, or in response to, periods of rainfall |                                                                                                                                        |
| DPGR   | Dry period groundwater recharge system during periods without rainfall | Volume of water moving vertically from the wetland into the underlying groundwater                                                     |
| BASE FLOW AND LOW FLOWS                   |                                                            |                                                                                                                                        |
| GDS    | Groundwater discharge site                                | Movement of groundwater into surface water through the wetland                                                                       |
| DPFV   | Dry period flow volume                                    | Volume of flow during dry periods                                                                                                      |
| DPFD   | Dry period flow duration                                  | Duration for which flow is sustained during dry periods                                                                                |
| DPRR   | Dry period recession rate                                 | Rate of flow recession during periods without rain; a high rate indicates a rapid decrease in flow, a low rate indicates sustained low flows |
| FLOOD RESPONSE                            |                                                            |                                                                                                                                        |
| FPLM   | Flood peak of low return period                           | Peak flow during a flood event, where the flow is exceeded on average                                                                   |
| (T <2 years)                              |                                                            |                                                                                                                                        |
| FPHM   | Flood peak of high return period                          | Peak flow during a flood event, where the flow is exceeded on average                                                                   |
| (T > 2 years)                             |                                                            |                                                                                                                                        |
| FEV    | Flood event volume                                        | Total volume of flow during an individual flood event                                                                                 |
| FFTP   | Flood time-to-peak                                       | Time between the onset and peak of a flood event                                                                                       |
| FRR    | Flood recession rate                                      | The recession rate of a flood event                                                                                                    |
| RIVER FLOW VARIABILITY                    |                                                            |                                                                                                                                        |
| FVa    | Flow variability                                          | Flow variability within the full flow regime                                                                                           |
| WPFV   | Wet period flow variability                               | Flow variability during, or in response to, periods with rainfall                                                                     |
| DPFV   | Dry period flow variability                               | Flow variability during periods without rainfall                                                                                       |

the focus of studies on North America. Consequently, one cannot necessarily transfer the results of this study to the general grouping of ‘worldwide wetlands’. (5) Conclusions are presented as stated in the original paper; no attempt is made to evaluate or uphold the conclusions that are drawn. Further work in the critical evaluation of past studies would represent a valuable contribution to the science of wetland hydrology. (6) No attempt has been made at cross-correlation of hydrological measures within single studies. For example, if a study has concluded that a particular wetland increases evaporation, no conclusion is drawn that flow is reduced, unless that explicit statement is made by the author.
Table 5

### a. Gross water balance

|                      | FP | SW/D | SW/S | GW/D | GW/S | General | Total |
|----------------------|----|------|------|------|------|---------|-------|
| **Mean annual flow** | MAF| +    | 2    | 8    | 1    | 2       | 4     |
|                      |    | -    |      | 1    | 5    | 1       | 23    |
|                      |    |      |      | 1    | 7    | 1       | 23    |
| **Mean annual actual evaporation** | MAAE| +    | 8    | 4    | 1    | 6       | 21    |
|                      |    | -    |      | 1    | 2    | 1       | 3     |
|                      |    |      |      | 1    | 2    | 1       | 3     |
| **Wet period flow**  | WPF| +    | 1    | 3    | 5    | 6       | 15    |
|                      |    | -    |      | 1    | 2    | 2       | 5     |
|                      |    |      |      | 1    | 1    | 1       | 4     |
| **Wet period actual evaporation** | WPAE| +    | 1    | 1    | 1     | 1      |
|                      |    | -    |      | 1    | 1    | 1       |
|                      |    |      |      | 1    |
| **Dry period actual evaporation** | DPAE| +    | 4    | 3    | 15    |         |
|                      |    | -    |      | 1    | 1    |         |
|                      |    |      |      |      |      |         |
| increased flow or reduced evaporation |   | 3    | 0    | 4    | 1    | 11      | 6     |
| reduced flow or increased evaporation |   | 25   | 2    | 12   | 2    | 30      | 5     |
| not increased or reduced |   | 4    | 3    | 5    | 1    | 9       | 1     |

### b. Groundwater recharge

|                      | FP | SW/D | SW/S | GW/D | GW/S | General | Total |
|----------------------|----|------|------|------|------|---------|-------|
| **Annual groundwater recharge** | AGR| +    | 1    | 7    | 1    | 2       | 5     |
|                      |    | -    |      | 1    | 1    | 1       |
|                      |    |      |      | 1    | 1    | 1       |
|                      |    |      |      | 1    |
| **Wet period groundwater recharge** | WPGR| +    | 1    | 1    | 1     | 1      |
|                      |    | -    |      | 1    | 1    |
|                      |    |      |      | 1    |
|                      |    |      |      |      |      |         |
| increased recharge | 1  | 1    | 0    | 1    | 2    | 1       | 6     |
| decreased recharge | 1  | 1    | 3    | 0    | 0    | 4       | 9     |
| not increased or decreased | 0  | 0    | 2    | 1    | 1    | 0       | 4     |
| recharge does not occur | 1  | 2    | 5    | 1    | 7    | 2       | 18    |
| recharge occurs | 9  | 6    | 3    | 5    | 7    | 2       | 32    |

### c. Base flow and low flow

|                      | FP | SW/D | SW/S | GW/D | GW/S | General | Total |
|----------------------|----|------|------|------|------|---------|-------|
| **Groundwater discharge site** | GDS| =    | 2    | 4    | 3    | 18      | 27    |
|                      | X  | 2    | 2    | 1    |      |         | 5     |
| **Dry period flow volume** | DPFV| +    | 3    | 1    | 1    | 6       | 14    |
|                      | -  | 5    | 11   | 1    | 22    | 8       | 47    |
|                      |    | 1    | 4    | 1    | 2    | 2       | 10    |
| **Dry period flow duration** | DPFD| +    |      | 1    | 1    |         | 2     |
|                      | -  |      |      | 1    | 1    |         |
|                      |    |      |      |      |      |         |
| low flows sustained | 3  | 1    | 1    | 0    | 7    | 4       | 16    |
| low flows diminished | 5  | 0    | 12   | 1    | 23    | 8       | 49    |
| not sustained or diminished | 1  | 0    | 4    | 1    | 2    | 2       | 10    |
| groundwater discharge does not occur | 0  | 2    | 2    | 1    | 0    | 0       | 5     |
| groundwater discharge occurs | 2  | 4    | 0    | 3    | 18   | 0       | 27    |
### d. Flood response

| Category                                    | FP | SW/D | SW/S | GW/D | GW/S | General | Total |
|---------------------------------------------|----|------|------|------|------|---------|-------|
| Floodpeak low magnitude (T<5 yrs)           | FPLM | +    | 1    | 7    | 2    | 1       | 11    |
|                                             |    | -    | 12   | 1    | 1    | 10      | 38    |
| Floodpeak high magnitude (T<5 yrs)          | FPHM | +    | 2    | 3    | 2    | 9       | 9     |
|                                             |    | -    | 4    | 1    | 1    | 1       | 8     |
| Flood event volume                          | FEV | +    | 1    | 3    | 6    | 1       | 11    |
|                                             |    | -    | 4    | 1    | 3    | 1       | 9     |
| Flood time to peak                          | FTTM | +    | 3    | 2    | 1    | 6       | 6     |
|                                             |    | -    | 1    | 1    | 1    | 1       | 1     |
| Flood recession rate                        | FRR | +    | 5    | 3    | 8    | 8       | 8     |
|                                             |    | -    | 15   | 0    | 12   | 2       | 32    |
| Floods increased or advanced or recession reduced |      |      |      |      |      |         |       |
| Floods reduced or delayed or recession increased |      |      |      |      |      |         |       |
| not increase, reduced, delayed or advanced  |      |      |      |      |      |         |       |

### e. River flow variability

| Category                                    | FP | SW/D | SW/S | GW/D | GW/S | General | Total |
|---------------------------------------------|----|------|------|------|------|---------|-------|
| Flow variability                            | FVa | +    | 5    | 4    | 1    | 10      | 10    |
|                                             |    | -    | 6    | 1    | 2    | 0       | 10    |
|                                             |    |      | 1    | 3    | 2    | 6       | 6     |
| Wet period flow variability                 | WPFVa | +    | 1    | 1    | 1    | 2       | 2     |
|                                             |    | -    | 2    | 0    | 0    | 0       | 0     |
| Dry period flow variability                 | DPFVa | +    | 0    | 0    | 0    | 0       | 0     |
|                                             |    |      | 0    | 0    | 1    | 12      | 12    |
|                                             |    |      | 6    | 1    | 2    | 0       | 10    |
|                                             |    |      | 1    | 0    | 3    | 0       | 6     |

The association between hydrological types and local terms is presented in Table 6. It is immediately evident that there is no strong linkage between hydrological categorisation as applied in this paper and the use of local or ecological wetland terms; the terms peat, bog, marsh (and several others) recur in different hydrological types. Thus, grouping by hydrological type is seen as more meaningful than grouping by local terms. For example, the term ‘bog’ can be found in all five hydrological types.

From a hydrological perspective, the content of the database may be perceived as limited due to its emphasis on functions rather than hydrological processes — given that the concept of functions is not well-established within the hydrological community. However, while more process information can be extracted from the set of publications, the target of this paper is the use of functional generalisations to represent wetland hydrology to the wetland management and policy arena. Clearly, there is a strong case for bringing hydrological processes and function closer together.

Geographically, the dataset is dominated by 92 studies from North America (including 23 different U.S. States and six Canadian Provinces/Territories), with additionally 33 studies from 14 countries in Europe, 27 studies from 10 countries in Africa and 17 from elsewhere (including New Zealand (2), Australia, Brazil (3), India, Indonesia and Malaysia). This distribution reflects the substantial investment in scientific enquiry in North America compared with other regions of the world and a relative dearth of accessible information relating to Asian and South American wetland hydrology.

The term ‘wetland’ embraces a wide variety of land types, from springs to large inland deltas. As a result, a lack of consistency in the impact of wetlands on the water cycle was anticipated. Unique conclusions concerning any specific hydrological function cannot be drawn for all wetlands. Taking flow variability as a single hydrological measure, for example, there are 28 statements with good geographical coverage, of which 10 show that variability is increased by wetlands, 11 that variability is reduced, and 6 that wetland influence is neutral. When wetlands are sub-divided into
hydrologically similar types, greater consistency of conclusion emerges — six of seven conclusions from studies of floodplains conclude that flow variability is reduced by wetlands (including the Sudd and Okavango in Africa and Barito in Indonesia). But ambiguity still exists: amongst 19 studies of headwater wetlands (all from USA and Europe), 10 studies conclude that flow variability is increased; 5 that the wetland influence is neutral; and 4 that variability is reduced. Even apparently similar wetlands perform functions that are seemingly in opposition (e.g. peat bogs occur in each of the three categories; increasing, decreasing and not-affecting flow variability). But unanimity of function is not anticipated — there is no prior assumption that all wetlands of a particular type perform the same function. This study has not yet investigated the detailed climatology, catchment conditions and internal wetland structure, any of which can mean a particular wetland will perform differently from other wetlands that are otherwise similar.

Whether hydrological functions of wetlands are considered to be beneficial or not depends upon one’s point of view. For example, ecologists may see evaporation from wetlands as an essential process supporting plant growth, whilst water resource managers may see it as a loss of a vital downstream resource. Those living in flood-prone areas downstream of wetlands that generate floods may view them negatively while those living downstream of wetlands that reduce floods may not view them in the same light. Ecologists see floods as essential elements of the river flow regime maintaining channel structure through sediment transport, and interactions between the river and its floodplain that drives nutrient exchange and breeding cycles (Junk et al., 1989, Poff et al., 1997).

The main conclusions of the analysis are as follows.

1. Wetlands are significant in altering the water cycle. The 169 scientific studies published during the period 1930–2002 (as traced by this paper) provide 439 statements on the hydrological significance of wetlands. Of the 439 statements, only 83 (19%) conclude the wetland influence on the water cycle to be neutral or insignificant. The vast majority conclude that wetlands either increase or decrease a particular component of the water cycle. It is this evidence that has led to the notion that wetlands perform hydrological functions. Since wetlands cover approximately 6% of the world’s land area, with many linked directly to rivers and aquifers, this is an issue of importance to water management.

2. There are some significant generalisations that emerge from the published hydrological evidence. These are different from the long-standing generalisation that wetlands always reduce floods, promote groundwater recharge and regulate river flows. Most, but not all, studies (23 of 28) show that floodplain wetlands reduce or delay floods, with examples from all regions of the world. This same influence on floods is also seen, but less conclusively (30 of 66) for wetlands in the headwaters of river systems (e.g. bogs and river margins). A substantial number (27 of 66) of headwater wetlands increases flood peaks. These studies were mostly from Europe, but included work from West Africa and Southern Africa. Around half of the statements (11 of 20) for flood event volumes and 8 of 13 for wet period flows) show that headwater wetlands increase the immediate response of rivers to rainfall,
generating higher volumes of flood flow, even if the flood peak is not increased. The coverage of these studies is world-wide including Africa and South America. This function occurs because headwater wetlands tend to be saturated and convey rainfall rapidly to the river; thus they are a principal mechanism for generation of flood flows.

3. There is strong evidence that wetlands evaporate more water that other land types, such as forests, savanna grassland or arable land. Two thirds of studies (48 of 74) conclude that wetlands increase average annual evaporation or reduce average annual river flow. About 10% of studies (7) conclude the opposite; for example some woodlands in Zambia had greater evaporation than the adjacent wetlands. The remaining 25% are neutral. There is no obvious distinction amongst different wetland sub-types or geographical regions of the world.

4. Two-thirds of studies (47 of 71) conclude that wetlands reduce the flow of water in downstream rivers during dry periods. Evidence is mainly from North America and Europe, but includes floodplains in Sierra Leone and wetlands in Southern Africa. This is backed by overwhelming evidence (22 of 23 studies) that shows evaporation from wetlands to be higher than from non-wetland portions of the catchment during dry periods. There is no discernible difference for different wetland sub-types. In 20% of cases, wetlands increase river flows during the dry season.

5. Many wetlands exist because they overlie impermeable soils or rocks and there is little interaction with groundwater. The database contains 69 statements referring to groundwater recharge; 32 conclude merely that recharge takes place, and 18 conclude there is no recharge. There are similar numbers of studies that report wetlands either to recharge more (6) or less than (9) other land types. Some wetlands, such as floodplains in India and West Africa on sandy soils, recharge groundwater when flooded. Many wetlands have formed at springs and are fed by groundwater. The direction of water movement between the wetland and the ground may change in the same wetland, such as in some peatlands in Madagascar, according to hydrological conditions.

6. Conclusions have been drawn above on flow variability. The over-riding picture appears to be a reduction in flood peaks by floodplains. In some cases, such as many headwater wetlands, increasing flood flows combines with decreasing dry season flows to widen the overall range of flows.

Implications of the results for wetland research and policy formulation

This paper confirms that wetlands exert a strong influence on the hydrological cycle. It strengthens the view that management of wetlands must be an important part of integrated water resources and flood management of all river basins. Where wetlands reduce floods, recharge groundwater and increase dry season flows, wetland hydrology is working in sympathy with water resources managers and flood defence engineers. Where wetlands have high evaporation demands or generate flood-runoff, they may create or exacerbate water management problems. Whatever the hydrological functions they perform, decisions on wetland conservation will inevitably be taken in a wider context and will also depend on water scarcity and on other functions, such as human health, fisheries, navigation, recreation, cultural heritage and biodiversity.

Successful water management requires knowledge of the extent to which wetlands are performing different hydrological functions. Since it is not feasible to study every wetland in detail, rapid assessment methods are required to identify likely functions. Furthermore, a major objective of this work is to stimulate discussion on hydrological functions. It is relatively easy to add to the database, either within additional previously published work or through new research. It is harder to account for variations in functions. For it is clear that there is no simple relationship between wetland types and the hydrological functions they perform. Part of the problem stems from the lack of a simple classification of wetlands that consistently relates hydrology, vegetation, substrate type and geomorphology. It is unlikely that any sophisticated classification scheme would be able to explain the variation of function in evidence.

Various methods have been developed in a number of countries around the world to assess hydrological functions of wetlands. Some are merely classification systems that group wetlands according to botanical, geomorphological and/or water regime characteristics (e.g. Cowardine et al., 1979; Brinson, 1993; Gilvear and McInnes, 1994; Wheeler, 1984). Other methods give each wetland a grade for a function, such as high medium or low (e.g. Adamus et al., 1987) or produce a quantitative estimate of performance of a given function (e.g. Amman and Stone, 1991; Hruby et al., 1995). Malby et al. (1996) have developed a framework of functional analysis through characterisation of distinct ecosystem/landscape units (termed hydrogeomorphic units). The objective is to provide a simple and rapid procedure, but the system still needs to be operationalised. In addition, guides have been produced for extending the functional assessment to produce an economic value for the functions.
(Lipton et al., 1995, Barbier et al., 1995). Recent work in the UK (Wheeler and Shaw, 2000) used data from over 80 wetlands in Eastern England to develop a classification and assessment system called WETMECS that combines landscape situation, water supply mechanism, hydrotopographical elements, acidity (base-richness) and fertility. The outcome of this study is that apparently similar wetlands are driven by very different hydrological processes; almost invariably, some data need to be collected at a site to identify its functional role.

Consequently, generalised and simplified statements of wetland function are discouraged because they demonstrably have little practical value. As a minimum, this paper encourages the future representation of diversity and complexity amongst wetlands and the portrayal of diverse hydrological functions.

Hydrologists must be more imaginative and proactive in contributing scientific knowledge to underpin policy formulation and management decisions. For the hydrological community, a new challenge is set for wetland policy.

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### Annex 1

**GLOBAL REVIEW OF WETLAND WATER QUANTITY FUNCTIONS**

| Author | Country (state, province) | Wetland type | Local term | Basis of inference | Category of study | Summary of functional statement | Function summary |
|--------|---------------------------|--------------|------------|-------------------|------------------|--------------------------------|-----------------|
| Hurst (1933) | Sudan | FP | Sudd | In-Out | LTH | FVa: swamp discharge varies very little; fluctuations are rapidly damped out MAAE: 14 million of flow is lost in the swamps (p.731-2) | FVa: - MAAE: + |
| Vecchioli et al. (1962) | New Jersey, USA | GW/S | Swamp, marsh | In-out | LTH | DPFV: baseflow is reduced to 75% of the input ... DPAE: ... by high summer evapotranspiration MAF: swamplands have little effect on the total flow FPLM: the swamp decreases the downstream floods FEV: seasonal runoff is greater than that of the upland (p.699-700) | DPFV: - DPAE: + MAF: . FPLM: - FEV: + |
| Riggs (1964) | N. Carolina, Tennessee, USA | General | Swamp | Paired | LTH | DPRR: comparison of a flat recession for the swampy Haw, with a steep recession of the non-wetland New River (p.359). | DPRR: + |
| Meyboom (1964) | Saskatchewan, Canada | GW/S | River valley | CompV | SEH | DPFV: 70% of flow depletion can be accounted for by phreatophytic vegetation (p.254) | DPFV: - |
| Meyboom (1966) | Saskatchewan, Canada | GW/D | Prairie pothole | CompGW | CompGW | AGR: “Groundwater was recharged during the period of study” (p.60) | AGR: + |
| Miller (1965) | New Jersey, USA | GW/S | Swamp, marsh | In-out | WB | DPFV/DPAE: summer evapotranspiration causes a significant reduction in baseflow GDS: the swamp is an area of discharge for the regional groundwater body (p. B179) | DPFV: - DPAE: + GDS: = |
| Ackney et al. (1967) | Minnesota, USA | General | Swamp, bog, marsh | Multiple | LTH | DPFV: basins having lake or wetland areas in excess of 5% have more than twice as much annual groundwater runoff. (p.27) | DPFV: + |
| Bay (1967) | Minnesota, USA | SWIS | Perched bog | CompGW | CompGW | GDS: the water table reacts quite independently from the regional groundwater system (p.309) | GDS: X |
| Burke (1968) | Ireland | SWIS | Peat | Drained | WB | MAF: outflow is the same from drained and undrained area DPFV: flow eventually becomes zero from both areas FPLM: much higher peaks occur for the undrained area FTTP: the undrained area flows sooner than the drained area FRR: after flood peaks, the drained area is still discharging water at a faster rate WPFVa: sustained flows are more uniform in the drained area (p.B14-6) | MAF: . DPFV: . FPLM: + FTTP: + FRR: + WPFVa: + |
| Author                  | Region                  | Type          | Comparison | Flow          | Description                                                                                                                                                                                                 | Notes |
|------------------------|-------------------------|---------------|------------|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Romanov (1968)         | Former USSR             | SW/D          | Bogs       | Same          | MAAE/MAF: bog evaporation and runoff approaches that of unbogged areas. FVa: drainage of highmoor bogs causes the redistribution to become more marked. (p.232-3) |       |
| Shyflo (1968)          | N. Dakota, USA          | SW/D          | Prairie pothole | Comp<sub>gw</sub> | WB | WPG: it was assumed that no seepage took place during the winter months when the potholes were frozen (p. B48)                                                                                           | WPG: X |
| Williams (1968)        | Illinois, USA           | GW/D          | Marsh       | Comp<sub>gw</sub> | Comp<sub>gw</sub> | GDS/AGR: some marshes behave as groundwater sinks, others as a groundwater mound (p. 782)                                                                                                          | GDS: =  AGR: = |
| Bay (1969)             | Minnesota, USA          | SW/S          | Peat bog    | Same          | LTH | DPPD: storage was not available to sustain summer flow. FVa: bogs were not effective as streamflow regulators. FPLM/FRR: low peak flows and long-drawn out recessions suggest that the bogs do store short-term runoff (p. 101) | DPPD: -  FVa: -  FPLM: -  FRR: - |
| Freeze (1969)          | Saskatchewan, Canada    | SW/D          | Slough      | Comp<sub>gw</sub> | Chem | DPGR: among 76 bogs 27 are classified as 'Fast Recharge', 10 as 'Slow Recharge' and 39 do not recharge. GDS: 14 are classified as 'Fast discharging sloughs', 10 as 'Slow Discharging sloughs', 50 do not discharge. (p. 12-14) | DPGR: =  GDS: =  GDS: X |
| Campbell & Drecher (1970) in Novitski (1985) | Wisconsin, USA         | General       | Basin storage | Multiple      | LTH | WPF/AGR/DPFV: in basins with large lake and wetland area, more water runs off in spring and only a small amount recharges the aquifer; thus base flow is reduced in summer, fall and winter (Novitski, p. 147) | WPF: +  AGR: -  DPFV: - |
| Darmer (1970) in Novitski (1985) | New York, USA          | General       | Lakes and ponds | Multiple      | LTH | FPHM: basin storage is statistically insignificant in explaining the variability of flood peaks (T = 20 yrs). AGR/DPFV: large percentage of storage in basins results in reduced recharge and consequently reduced baseflow (Novitski, p. 145-5) | FPHM: .  AGR: -  DPFV: - |
| Forest & Walker (1970) in Novitski (1985) | Delaware, Maryland, USA | General       | Basin storage | Multiple      | LTH | FPHM: basin storage is statistically insignificant in explaining the variability of flood peaks (T = 5-100 yrs). AGR/WPF/DPFV: spring runoff is greater and recharge to groundwater and baseflow lower in basins with a larger percentage of lake and wetland area (Novitski, p.145-9) | FPHM: .  AGR: -  WPF: +  DPFV: - |
| Nuckles (1970) in Novitski (1985) | Virginia, USA          | General       | Basin storage | Multiple      | LTH | FPHM: basin storage is statistically insignificant in explaining the variability of flood peaks (T = 5-100 yrs). WPF/DPFV: annual minimum series are lower for basins with large percentages of lakes and wetlands (Novitski, p.149) | FPHM: .  WPF: +  DPFV: - |
| Wharton (1970)         | Georgia, USA            | FP            | Swamp       | Paired        | LTH | FPLM: a comparison of Alcovy (swamp) and Yellow hydrographs suggests a damping influence. FTTTP: peaks of the Alcovy lag 24 hours behind the Yellow. FVa: Alcovy flow duration curves are smooth and many minor fluctuations shown for the Yellow are missing. It is likely that the Alcovy (alluvial) aquifer beneath the floodplain does strongly influence the variability of base flow. DPFV: although the Yellow drains an area 36% larger, its low flows are close to those of the Alcovy, suggesting some possible influence of the swamp on base flow (p.15-18). | FPLM: -  FTTTP: -  FVa: .  DPFV: + |
| Author               | Year       | Study Location                         | Wetland Type | Multiple LTH | General Basin Storage | FPHM | DPFV | DPAE | GDS | MAF | WPF | FRR | MAAE | DPFD | DPRR |
|---------------------|------------|----------------------------------------|---------------|---------------|-----------------------|------|------|------|-----|-----|-----|-----|------|------|------|
| Conger, Novitski    | 1971       | Wisconsin, USA                         | General       | No             | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| Kloet, Bardecki     | 1971       | North Dakota, USA & Manitoba, Canada   | General       | Yes            | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| Kloet, Bardecki     | 1987       | North Dakota, USA & Manitoba, Canada   | General       | Yes            | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| Millar              | 1971       | Canada                                 | Prairie Pothode | Yes            | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| McComas et al.      | 1972       | Illinois, USA                          | Bog           | No             | No                    | No   | No   | No   | No  | No  | No  | No  | No  | No   | No   | No   |
| Stewart & Kantrud   | 1972       | North Dakota, USA                      | Prairie Pothode | Yes            | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| Balek & Perry       | 1973       | Zambia                                 | Dambo         | Yes            | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| Wilson & Wiser      | 1974       | South Carolina, USA                    | Floodplain    | Yes            | Yes                   | Yes  | No   | Yes  | Yes | Yes | Yes | Yes | Yes | No   | Yes  | No   |
| Bavina              | 1975       | European USSR                          | Swamp         | No             | No                    | No   | No   | No   | No  | No  | No  | No  | No  | No   | No   | No   |
| Authors            | Location          | Type         | Drained | Method | Results                                                                 |
|--------------------|-------------------|--------------|---------|--------|-------------------------------------------------------------------------|
| Bulavko & Drozd    | USSR              | General Peat | Drained | LTH    | MAF/MAAE: initially after drainage annual runoff is increased due to a decrease in evapotranspiration<br>WPF: spring flows either increase or decrease<br>DPFV: minimum and summer low flows increase considerably<br>FVa: the proportion of the groundwater contribution to flow increases, improving the distribution of river runoff (p.466) |
| Burke             | Ireland           | SW/S Blanket peat | Drained | WB     | MAF/FVA/FEV: the drained area runoff was 60% greater than the undrained area. Flow was much more uniform and did not show the sharp peaks evident in the undrained area<br>AGR: some seepage may occur, albeit small, but both peat and the subsoil have extremely low permeability<br>FPLM/DPFV: after drainage, floods will be reduced in frequency and amount and summer flow of streams will be increased in the short-term (p.176) |
| Eggelmann         | Germany           | SW/S Peat    | Same    | WB     | MAAE/MAF: there is higher evaporation from peat and reduction of runoff with respect to mineral soils<br>FVa: there is no causal relations between the steady runoff and the water storage of peat (p.359) |
| Eisenlohr          | N. Dakota, USA    | GW/D Prairie Pothole | CompGW CompGW | AGR: although there is evidence that a very small portion of seepage moves vertically downward, most of the seepage outflow moves laterally (p.309) |
| Glazacheva        | Latvia            | General Marsh | Drained | LTH    | FVA/FIR/MDFPV: river flow variability increased following drainage as the maximum discharges increased and the minimum decreased (p.514) |
| Hommik & Madisson  | Estonia           | GW/S Fen bogs | Drained | WB     | MAF: annual runoff from drained fen bogs increases by 92mm (p.489) |
| Kiselev           | Byelarus           | GW/S Swamp   | CompGW CompGW | AGR/GDS: swamps may be supplied by groundwater and may also serve as sources of groundwater recharge (p.38-40) |
| Klueva            | Byelorussia       | SW/S Marsh   | Drained | LTH    | DPFV: the minimum discharge increased by 30-150%<br>FPLM: maximum discharges decreased by 17-30% on 7 basins; in other basins no significant change occurred<br>FTTP: no significant changes were observed in the timing of the snowmelt flood, or in the date of the peak<br>FVa: 6 basins were characterised by decrease of spring flow of 10 to 30%; summer and autumn flow increased 20 to 60%<br>MAF: MAF of 9 basins increased by 10 to 20%. On the other 7 basins there was no significant change (p.424-6). |
| Molyakov et al.   | Ukraine           | FP Marsh     | Drained | LTH    | MAF: runoff tends to decrease after drainage<br>WPF: decrease in spring flows is generally found but cases are encountered where the flow is unchanged or tends to increase<br>FPLM: drainage does not always affect the maximum discharge, although it may either decrease or increase (p.442) |
| Mikulski & Lemiesz| N. E. Poland      | GW/S Peat bog | Drained | WB     | MAAE: evaporation decreased by about 15% as compared with the pre-reclamation period<br>MAF/WPF/DPFV: results show a 20% increase in runoff, as compared to the pre-reclamation period... there were increases in the runoff, in summer and autumn (p.59) |
| Study                  | Country   | Type | Condition | Process | Description                                                                 | Results |
|-----------------------|-----------|------|-----------|---------|-----------------------------------------------------------------------------|---------|
| Mustonen & Seuna (1975) | Finland   | SW/S | Peat      | Drained | LTH, MAAE/MAF: decrease in evapotranspiration led to an increase in total runoff. FPLM: an acceleration of flow caused by the drainage network led to an increase in maximum runoff. DPFV: the minimum runoff for both winter and summer increased markedly (p.523). | MAAE: + MAF: - FPLM: - DPFV: - |
| NERC (1975)            | UK        | FP   | Floodplain | In-out  | SEH, FPLM/FPHM: the most important change induced by a large floodplain on the shape of a flood hydrograph is the attenuation of the peak discharge (p.9). | FPLM: - FPHM: - |
| Smith (1975)           | Florida, USA | FP   | Cypress swamp | Same     | Compgw, AGR: days between the water table and the Floridan aquifer allow virtually no vertical movement. MAAE: vegetation is acting as a pump, removing water from the water table via transpiration (p.128-135). | AGR: X MAAE: + |
| Verry & Boeker (1975)  | Minnesota, USA | GW/S | Lake-filled bog | Same     | LTH, SEH, FVa: the groundwater bog has no regulating effect. FPLM: the bog does reduce storm flow peaks. FPHM: maximum peaks are independent of the bog. FRR: the bog delays the release of storm flow (p.472). | FVa: - FPLM: - FPHM: - FRR: - |
| Zivert et al. (1975)   | USSR      | BW   | Fen bog     | Same     | WPF, MAF/WPVa: in fen bogs drainage flow is 20 to 40% greater than mineral soils. The hydrograph of flood discharge is more uniform in peat than in mineral soils (p.121). | MAF: + WPVa: - |
| Heikuranen (1976)      | Finland   | SW/S | Peat      | Drained | WB, WPF: peak flow caused was considerably lower on the drained peatland. FTTTP: the flood from the drained peatland began earlier and lasted longer. DPFV: peak flow of the former remained lower. DPFV: runoff from the drained peatland during the dry summer was greater. FRR: flood from the drained peat began earlier and lasted longer (p.84-5). | WPF: + FTTTP: + FPLM: - DPFV: - FRR: - |
| Zivert et al. (1975)   | USSR      | BW   | Fen bog     | Same     | WPF, MAF/WPVa: in fen bogs drainage flow is 20 to 40% greater than mineral soils. The hydrograph of flood discharge is more uniform in peat than in mineral soils (p.121). | MAF: + WPVa: - |
| Sander (1976)          | Minnesota, USA | GW/S | Bog         | In-out   | WB /CCM, FVa: the bog's chief role is to superimpose a significant seasonal fluctuation on discharge. WPF: the bog releases excess water during wet periods. DPFV/DPAE: the bog depletes available supplies during dry periods through evapotranspiration. GDS: the wetland receives water from groundwater (p.35). | FVa: + WPF: + DPFV: - DPAE: + GDS: |
| Wilson & Dincer (1976) | Botswana   | FP   | Delta      | In-out   | WB, MAAE/MAF: outflow in the Boteti amounts to only 2% of inflow due to the evapotranspiration losses (p.36). | MAAE: + MAF: - |
| Balek (1977)           | Zambia    | GW/S | Dambbo    | Same     | WB/ CCM, FRR: the duration of the surface runoff is prolonged until early June (p.159). | FRR: - |
| Boeker & Verry (1977)  | Northern Lake States, USA | SW/S | Perched peat bog | Compgw  | WB, DPFV/DPAE:AGR: late spring, summer and early fall evapotranspiration is at the expense of flow and deep seepage; peatland does not sustain streamflow during dry summer months by slowly releasing stored water. FRR: stormflows are modified by peatland. Storm hydrographs have long-drawn out recession curves. FPLM: peatland does reduce the peak rates of flow. FVa: neither bogs nor fens maintain an even distribution of streamflow (p.14-18). | DPFV: - DPAE: + AGR: - FRR: - FPLM: - FVa: + |
| GW/S | Groundwater peat fen | CompGW | WB | FVa/FWP/DPFV/DPAE: instead of regulating flow, the fen may do the opposite by releasing excess water more quickly than mineral aquifers during periods of high precipitation and losing more water by evapotranspiration during dry periods (p. 15-16) | FVa: + WPF: + DPFV: - DPAE: + |
|---|---|---|---|---|---|
| Flippo (1977) in Novitski (1985) | Pennsylvania, USA | General | Basin storage | Multiple | LTH | FPHM: basin storage is statistically insignificant in explaining the variability of flood peaks (T = 5-100 yrs) (p.145) | FPHM: |
| Hidek et al. (1977) | Minnesota, USA | GW/S | Wetland | Same | WB | AGR/GDS: the wetland is a point of discharge for the local glacial till. Groundwater losses are considered zero. DPFV: the wetland reduced minimum flow to less than the estimated base flow (p.46) | AGR: X GDS: = DPFV: - |
| Littlejohn (1977) | Florida, USA | FP | Cypress swamp | Drained | CCM | FVa: retention of cypress swamps contribute to greater stability of water regimes (p.472) | FVa: - |
| Mitsch et al. (1977) | Illinois, USA | FP | Forest swamp | Same | WB | FEV: water retained by the swamp is 7.8% of an individual event. No effect was seen on any other storm occurrences DPFV: flow maintenance can be very significant (p.77-89) | FEV: - FEV: + DPFV: + |
| O'Brien (1977) | Massachusetts, USA | GW/S | Peat | Paired, Same | WB, LTH | WPAE: spring evapotranspiration is depressed relative to non-wetland WPF: the wetland was responsible for high spring flows DPAE: fall rates are high relative to non-wetland areas DPFV: baseflow during the low flow period was greatly depressed GDS: the wetland receives water from the regional groundwater body (p.336-338) | WPAE: - WPF: + DPAE: + DPFV: - GDS: = |
| Littlejohn (1977) | Florida, USA | FP | Cypress swamp | Drained | CCM | WPAE: spring evapotranspiration is depressed relative to non-wetland WPF: the wetland was responsible for high spring flows DPAE: fall rates are high relative to non-wetland areas DPFV: baseflow during the low flow period was greatly depressed DPGR: during summer the swamp recharges groundwater (p.336-8) | WPAE: - WPF: + DPAE: + DPFV: - DPGR: = |
| Winner & Simmons (1977) | North Carolina, USA | FP | Floodplain swamp | Drained | LTH | FPLM/FPV/MF: higher flows (> 5 exceedance-percentage) increase; low flows increase. Total runoff would not change (p.53) | FPLM: - DPFV: - MF: |
| Novitski (1978) | Wisconsin, USA | General | Wetland and lake | Multiple | LTH | FPLM: flows may be 80% lower in basins with much wetland and lake WPF: more spring runoff occurs in basins with much wetland and lake AGR/DPV: less groundwater recharge (and baseflow) occurs in basins with much lake and wetland (p.384-6) | FPLM: - WPF: + AGR: - DPFV: - |
| Verry & Boecher (1978) | Minnesota, USA | GW/S | Fen | Same | WB | AGR: the GW/S fen does not discharge through the peat (p.398) | AGR: x |
| McKay et al. (1979) | Illinois, USA | GW/S | Swamp | CompGW | WB | GDS: the volume of (ground-) water annually entering the swamp by discharge from the bedrock is quite large (p.31). | GDS: = |
| Authors | Location | Type | Kind | Multiple | LTH | FPHM | DPFV | MAAE | MAF |
|---------|----------|------|------|----------|-----|------|------|------|-----|
| Drayton et al. (1980) | Malawi | FP | Dambo | Multiple | LTH | FPHM: dambo provides a lot of floodplain storage | DPFV: dambo catchments are not significantly distinguishable from unaffected neighbours for Q75 | MAAE/MAF: presence of dambo increases evaporation with a corresponding decrease in average annual yield (p. 58) |
| Hemond (1980) | Massachusetts, USA | SW/D | Kettle hole | In-out | WB | GDS: the bog is characterised by an absence of recharge (p. 522) |
| Hill & Kidd (1980) | Malawi | GW/S | Dambo | Multiple | LTH | MAAE/MAF: average annual runoff volume is reduced by 0.4 mm for every 1% of dambo (p. 16) |
| O'Brien (1980) | Massachusetts, USA | GW/S | Wetland | CompGW | LTH | WPF: groundwater was the major component of all flood peaks (rather than originating from the wetlands) (p. 39) |
| Bedinger (1980) | Mississippi, USA | FP | Floodplain | CompGW | LTH | FPLM: floodplains ameliorate downstream flooding | AGR: significant recharge occurs on floodplains (p. 168, 173) |
| Brown et al. (1981) | N. Dakota, USA | GW/D | Sloughs | Drained | TS | MAF/FPIM/DPFV: approximately 50% of the increase in flow, 36% of the increase in maximum flow, and 70% of the increase in spring flow is due to increased drainage (p. 13) |
| Daniel (1981) | N. Carolina, USA | GW/S | Pocosin | Drained | WB | FPLM: hydrographs from the Albemarle Canal show five floods while the wetland Van Swamp show none | DPFV/DPAE: from raised wetlands there is usually little discharge after June because of evaportranspiration |
| Gilliam & Skaggs (1981) | N. Carolina, USA | GW/S | Pocosin | Drained | WB | FPLM/FTTP: peaks are higher and earlier on developed sites | MAF: there was little difference in total flow (p. 115) |
| Newson (1981) | Wales, UK | GW/S | Peat | Same | SEH | DPFV: very low yields prevailed, excepting two headwater areas characterised by periglacial deposits and peat (p. 80). |
| Norton & Thorne (1981) | Brazil | FP | Floodplain | CompGW | WB | FEV: the dominant and rapid hydrograph response comes essentially from saturation overland flow on the floodplain (p. 54) |
| Sellars (1981) | Nigeria | FP | Floodplain | CompET | CCM | MAF/DPFV/AGR: losses in the Upper Yobe are 70% of MAF. Storage causes flooding to continue into the dry season. 10% of losses contribute to regional ground water (p. 267) |
| Novitski (1982) | Wisconsin, USA | SW/D | SW/D wetland | Same | WB | A surface-water depression wetland has ... | FPLM: ... an effect in reducing flood peaks | DPFV: ... some effect on increasing base flows | WPF: ... no effect on increasing spring time runoff | MAAE: ... some effect in increasing ET (p. 19-20) |
| Novitski (1982) | Wisconsin, USA | SW/S | SW/S wetland | Same | WB | A surface-water slope wetland has ... | FPLM: ... an effect in reducing flood peaks | DPFV: ... some effect on increasing base flows | WPF: ... increases spring time runoff | MAAE: ... no effect on ET (p. 19-20) |
| Novitski (1982) | Wisconsin, USA | GW/D | GW/D wetland | Same | WB | A ground-water depression wetland has ... | FPLM: ... an effect in reducing flood peaks | DPFV: ... no effect on increasing base flows | WPF: ... no effect on increasing spring time runoff | MAAE: ... an effect in increasing ET | AGR: some recharge occurs (p. 19-20) |
| Country | Region | Wetland/Soil | Hydrograph Type | Comp. | LTH | FPLM | DPFV | WPF | MAAE | Author | Year | Notes |
|---------|--------|--------------|----------------|-------|-----|------|------|-----|------|--------|------|-------|
| Minnesota, USA | SW/S | Peat | Same | WB | General | Wetland and lake | Multiple | LTH | FPLM: flood peaks are 80% lower in a basin with 40% lake and wetland area than in a basin with no lake or area (p.16) | Verry & Timmons (1982) | 1982 | |
| New Zealand | GW/S | Macrophytes | Comp | LTH | DPAE: distinct diurnal rhythms in hydrographs were caused by evaporative losses during the day, which could not be detected when the macrophyte growth was minimal (p.57) | Howard-Williams (1983) | 1983 | |
| N. Dakota, USA | SW/D | Shallow depressions | Multiple | LTH | MAF/FP/HM: the depressions store 72% of 2-yr return period flow and 41% of 100-year return period flow (p.45) | Ludden et al. (1983) | 1983 | |
| Natal, South Africa | FP | Marsh | Same | LTH | DPAE: recession hydrographs exhibit diurnal fluctuations with greater evapotranspirational losses in the riparian zone during the day (p. 88) | Seyhan et al. (1983) | 1983 | |
| Minnesota, USA | GW/S | Raised bogs | Fens | CompGW | AGR: recharge zones in the peats are the raised bogs, and the discharge zones are the adjacent fens. Precipitation on the fens does not enter the groundwater system (p. 918) | Siegel (1983) | 1983 | |
| Malawi | GW/S | Dambos | Same | WB | MAAE: actual annual evaporation losses from dambos is 640mm compared with 692mm from shallow interfluve and 760mm from wooded interfluve FEV: hydrographs show more flashy responses because there is less dambo area for temporary retention of water. DPPN/DPAE: high dambo evapotranspiration results in a decrease in flow rate and cessation of river flow (p.36). | Smith-Carrington (1983) | 1983 | |
| Florida, USA | GW/S | Cypress domes | CompGW | WB | AGR: usually Sewage Dome 2 recharges the groundwater. At Austin Cary there is little deep percolation as the underlying aquifer is artesian (p. 80). | Heimburg (1984) | 1984 | |
| S.W. Michigan, USA | GW/D | Peat bog | In-out | Chem | WPGR: bog waters are moving locally into groundwater DP/N: wetlands retain rain and incoming runoff and groundwater until it evaporates or percolates (p.839) | Keough & Popppe (1984) | 1984 | |
| Zambia | FP | Floodplain | Same | Comp | MAAE: evaporation from flooded areas on the Flats is considerably higher than from non-flooded areas (p.12-21) | Sharma (1984) | 1984 | |
| W. Africa | General | Hydromorphic/ gley soil | Same | Comp | FPLM: minimum rainfall required to produce runoff from hydromorphic/gley soils is lower than from ferrallitic soils FEV: on freely drained forest soils, no runoff occurs under rainfall of 120mm h^-1, while runoff attained 80% of input under rainfall of 30mm h^-1 on hydromorphic soils WP/AE/WPF: losses are far greater during severe floods where there are floodplains. In Mauritania, this represents almost 30% of the total flood volume AGR: when a stream disappears into its floodplain, the alluvial water table may be replenished (p.244-257) | Dubrulle (1985) | 1985 | |
| Author(s) | Location | Type | Drainage | Water Type | Notes |
|-----------|----------|------|----------|------------|-------|
| Millington (1985) | Sierra Leone | FP | Inland valley swamps and bogs | Same | LTH | DPFV: during the dry season, swamps retain surface water which is lost by evaporation and seepage (p.19) |
| Novitski (1985) | Northern and Eastern States, USA | General | Wetland and lake | Multiple | LTH | In basins with large percentages of lakes and wetlands... WPF: spring peaks are less DPFV: baseflow is less (p.151) |
| Baden & Egelsmann (1986) | Germany | SW/S | Raised bog | Drained | WB | FV: run-off of the predrained bog was more extreme FPLM/DPFV: run-off in downstream areas are such that the risk of highwater and dryness becomes smaller (p.206-8) |
| Gurnell & Gregory (1986) | England, UK | SW/S | Saturated heath | Same | LTH | FPLM: storm runoff volume can be related to the area of the catchment that is saturated or has a near-surface water table prior to a storm (p.94) |
| Ogawa & Male (1986) | Massachusetts, USA | FP | Wetland | Without CCM | WB | FPLM: the worth of an upstream wetland for flood mitigation is negligible. Downstream main-stem wetlands were more effective in reducing downstream flooding (p.114) |
| Roulet & Woo (1986) | NW Territories, Canada | GW/S | Peat | Comp | WB | DPFV/DPAE/FV: post-spring water loss is mainly due to evaporation and not lateral runoff. Wetlands do not play an important role in streamflow regulation (p.89) |
| Wilcox et al. (1986) | Indiana, USA | GW/S | Peat fen | Comp | WB | AGR: a water table in the peat mound causes a pattern of shallow groundwater flow away from the peat mound GDS: seepage through marl into peat is deduced (p.111) |
| Bardecki (1987) | S.W. Ontario, Canada | General | General | Drained | LTH | MAF/FPLM/DPFV: neither strong evidence nor clear suggestions of any change in flow attributable to drainage was found (p.127) |
| Doyle (1987) | Massachusetts, USA | FP | Floodplain | Paired | LTH | FPHM: maximum floods in the Charles are extremely low compared to the adjacent low wetland Blackstone river (p.111) |
| Ford & Bedford (1987) | Alaska, USA | General | General wetland | In-out | WB | AGR: the contribution of Alaskan wetlands to groundwater is probably negligible FPLM: during snowmelt, wetland soils do not contribute significantly to flood storage (p.209) |
| Jackson (1987) | South Island, New Zealand | GW/S | Pakihi wetland | Drained | WB | FE: natural undrained wetlands are highly responsive to rainfall. Over 70% of total annual runoff is quickflow DPFV: low flows increased after vegetation was removed, but decreased after draining FPHM: increased frequency of large peak flows is probably the most important impact of drainage works (p.471-3) |
| Robertson (1987) | Alaska, USA | General | General | Same | LTH | DPFV: wetlands contribute little to the mid-summer budget of tundra streams (p.267) |
| Woo & Heron (1987) | N. Ontario, Canada | GW/S | Bogs and fens | Comp | WB | GDS: meltwater from open bogs and fens is supplied by the local snow cover and from adjacent forested areas. Most of the runoff from the bog occurred as groundwater flow (p.303-4) |
| Author(s)                | Region                  | Type       | Treatment | LTH  | DPFV: the principal difference between raised bogs and till is groundwater levels in the bogs are always sufficiently high to provide the streams from these areas with runoff (p.90) | MAF: - FPLM: - |
|--------------------------|-------------------------|------------|-----------|------|----------------------------------------------------------------------------------------------------------------------------------|-----------------|
| Brandesten (1988)        | S.C. Sweden             | GW/S       | Mine      | Multiple | DPFV: +                                                                                                                          | MAF: - FPLM: - |
| Konyha et al. (1988)     | North Carolina, USA     | GW/S       | Peat      | Drained  | CCM MAF/FPLM: peat mining alone increases the annual runoff and peak outflow rates (p.490)                                                                                                  |                 |
| Kovrego & Yantsikho (1988) | Byelorusia              | SW/S       | Bog       | Drained  | WB MAAE: evaporation decreases 7-10% following drainage reclamation (p.24)                                                                                                               |                 |
| Kowalik et al. (1988)    | Poland                  | GW/S       | Peat      | Comp GW  | GDS: upward seepage is about 30% of rainfall (p.178)                                                                                                                                        |                 |
| Landin (1988)            | Sweden                  | GW/S       | Peat      | Drained  | WB MAF: drainage changed MAF insignificantly DPFV: low discharges generally increased  (p.204)                                                                                                 |                 |
| Moskvin (1988)           | West Siberia            | SW/S       | Palsa bogs| Same     | LTH DPFV: flow ceases completely in some weeks or months of the warm period due to low storage capacity AGR: there is a lack of losses by percolation into deep aquifers through saturated frozen peat layers (p.20-1) |                 |
| Niwala & Kuittinen (1988)| Finnish Lappland       | SW/S       | Aapa-mire | Same     | WB FEV: maximum runoff was caused by rapid runoff of the water from the mire (p.81)                                                                                                          |                 |
| Panu (1988)              | Newfoundland, Canada    | GW/S       | Peat      | Drained  | LTH FPLM: peak flows are increased by two to five folds DPFV: flow regime in the disturbed sub-basin experienced substantial changes such as decrease in low flows (p.295-6) |                 |
| Serban et al. (1988)     | Romania                 | GW/S       | Peat      | Paired   | LTH FEV: runoff in the peat basin is 30–35% lower than in the control (p.93-94)                                                                                                             |                 |
| Sharma (1988)            | Africa, Zambia          | GW/S       | Dambos    | Same     | WB MAAE: a ratio of ET/PET (Penman) equal to 1.5 is not surprising for tropical wetlands (p.38-39)                                                                                           |                 |
| Shichkimanov & Novikov   | Russia                  | GW/S       | Swamp     | Drained  | LTH MAF: drainage mainly increases MAF in the first years. There are some cases when MAF is reduced FPLM: high spring maxima tend to fall DPFV: minimum and summer runoff from swamps after drainage tends to increase FVa: drainage is manifested as more uniform and even flow distribution over seasons (p.69-71) |                 |
| Siegel (1988)            | Alaska, USA             | GW/S       | Blanket bog| Same     | CCM AGR/GDS/DPFV: wetland recharge and discharge are very small Groundwater discharge from wetlands is too small to measure (p.427)                                                          |                 |
| Verry (1988)             | Minnesota, USA          | GW/S       | Mine      | Same     | SEH FPHM: during large storms, peat looks like a reservoir - overland flow from the mineral soil was not observed (p.55)                                                                |                 |
| Brooks & Kroll (1989)    | Minnesota, USA          | GW/S       | Fen peat and bog | Drained  | CCM FEV: runoff is greater for mined peatlands than unmined DPFV: streamflow is generally reduced during summer months because of high evapotranspiration MAF: peat extraction in both bogs and fens appears to increase water yield over the short term (p.114-5) |                 |
| Author            | Region        | Type          | Study Type | Component | Data Source | Notes                                                                                                                                 |
|-------------------|---------------|---------------|------------|-----------|-------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Koerselman (1989) | Netherlands   | GWS           | Same WB    | GDS       | 31          | GDS: the fen is a focus for groundwater discharge (p.31)                                                                            |
| Stewart (1989)    | Zimbabwe      | GWS           | Same WB    | DPAE      |             | DPAE: the mean value of evaporation over all dambos regions over the 200 km² was estimated to be 3.5 mm d⁻¹ and 3.2 mm d⁻¹ for the area outside the dambos (p.48-59) |
| Sundiff & Parks (1989) | Colorado, USA | SW/S          | In-out LTH | FPLM      |             | FPLM: wetlands do not have a substantial affect on the magnitude of flood peaks. The wetlands may have a lesser ability to attenuate flood peaks than would upland areas. AGR: wetlands have no significant role in groundwater recharge (p.412) |
| Sutcliffe & Parks (1989) | Africa       | FP            | Floodplain | MAAE      |             | MAAE: losses in the Sudd and in the Niger are over half the annual inflow, in the lower Senegal are insignificant, and in the Okavango are a very high proportion of the inflows. FVa: Okavango and Sudd outflows are even less variable after damping (p.54-5) |
| Brown (1990)      | North America, USA | General Forest wetland | CompGW WB | AGR       |             | AGR: the bog and pocosin wetlands have virtually no recharge, the cypress dome experiences losses through infiltration or seepage (p.172-173) |
| Gehrels & Mulamoottil (1990) | S. Ontario, Canada | SW/S         | Wetland In-out WB | AGR       |             | AGR: recharge was found in the eastern portion of the wetland (p.225) |
| Hollis (1990)     | Nigeria       | FP            | Floodplain | LTH       |             | LTH: flood peaks decrease with increasing wetland area, and wetlands consistently increased low flows (p.949) |
| Demissie et al. (1991) | Illinois, USA | General Wetland Multiple LTH | FPLM       |             |             | FPLM: peak flows increase with increasing wetland area. FEV: flood volumes increase with increasing wetland area. DPFV: wetlands consistently increased low flows (p.1050) |
| Demissie & Khan (1991) | Illinois, USA | General Wetland Drained LTH | FPLM       |             |             | FPLM: in their pre-drained state, wetland reduced flooding. DPFV: in their pre-drained state, wetlands reduced low flows (p.313) |
| Faulkner & Lambert (1991) | Zimbabwe    | GWS           | Dambro Same WB | AGR       |             | AGR: total amount of water lost from the dambro to groundwater is small. DPAE: dry season evaporation was approximately 50% higher from the dambro than from dryland (p.153-5) |
| Hensel & Miller (1991) | Illinois, USA | GWS           | Pond In-out Comp GW | AGR       |             | AGR: seepage from the two ponds overlying impermeable till is insignificant. Seepage from the two ponds overlying permeable sand and gravel is large enough to double groundwater discharge (p.313) |
| Nieboe et al. (1991) | India        | FP            | Floodplain With-out CCM | FPLM |             | FPLM: upper groundwater recharge is due to large retention and infiltration losses on the wide sandy flood plains (p.274) |
| Robinson et al. (1991) | Germany     | GWS           | Peat Drained WB | MAF/MAAE/FPLM/DPFV |             | MAF: drainage of wetlands increased flows and reduced evapotranspiration losses. Peak flows were greater and low flows were higher (p.275) |
| Boeye & Verheyen (1992) | Belgium     | GW/D          | Fen CompeT WB | DPAE/DPFV |             | DPAE/DPFV: summer evapotranspiration is a major output - the water table drops and direct runoff disappears (p.161) |
| Author                  | Location          | Type   | Condition | Event Type | Measurement            | Notes                                                                 |
|-------------------------|-------------------|--------|-----------|------------|-------------------------|----------------------------------------------------------------------|
| Bullock (1992a)         | Zimbabwe          | GW/S   | Dambo     | Multiple   | LTH                     | MAF: dambos are an indiscrimatory factor in determining the volume, persistence and variability of annual runoff. DPFV: dambos do not maintain dry-season low flows and reduce low flows where they occur in association with regolith with significant baseflow components. FPHM: the impact of dambo on flood magnitude, variability and frequency is insignificant (p.349). |
| Bullock (1992b)         | Zimbabwe          | GW/S   | Dambo     | Same       | Comp<sub>ET</sub>       | DPAE: evaporation losses in August 1986 are 1 mm day<sup>-1</sup> higher on the dambo margins than the central dambo and interflow vegetation. (p.389) |
| Grillot & Dussarrat (1992) | Madagascar         | GW/S   | Peat      | Same       | WB                      | AGR/GDS: fluxes between aquifers vary between downward and upward directions during the year (p.321). |
| Klepper (1992)          | Indonesia         | FP     | Floodplain| Without    | CCM                     | FVA: the frequency distribution of river levels without swamps is considerably broader than the actual situation. MAF: without swamps, MAF decreases (p.322). |
| Price (1992)            | Newfoundland, Canada | SW/S   | Blanket bog| Same       | WB                      | AGR: 6% of losses was to groundwater seepage. FVA: pipe-flow and high near-stream gradients coupled with the high transmissivity produce a flashy gradient (p.103). |
| Bucher et al. (1993)    | Paraguay, S. America | FP     | Pantanal  | In-out     | LTH                     | FVA/MAAE/MAF: modification of the Pantanal may lose its condition as a natural sponge responsible for exceptional stability of flow. A faster passage of water may also decrease evapotranspiration and increase the amount of outflow (p.36). |
| Eggelhmann et al. (1993) | Germany            | SW/S   | Mires     | Paired     | WB                      | MAAE/MAF: mires are characterised by high evaporation and correspondingly low runoff relative to mineral soils. AGR: mires are not important in the regeneration of groundwater. Seepage rates from mires to deep groundwater is 80 to 50% lower in mires than in sandy soils (p.234-6). |
| Gibson et al. (1993)    | NW Territories, Canada | SW/S   | Wetland   | Comp<sub>WC</sub> | Chem                   | DPFV: wetland rivers commonly freeze by mid-October and negligible flows occur during winter (p.216). |
| Gilvear et al. (1993)   | England, U.K.     | GW/S   | Fen       | In-out     | WB                      | GDS: groundwater inflow accounted for about 90% of water inputs. FVA/DPAE/DPFV: seasonal pattern of wetland outflow mirrors that of groundwater inflow, though amplitude of change is greater because high evapotranspiration depletes surface outflow during the summer (p.325-6). |
| John et al. (1993)      | West Africa       | FP     | Floodplain| In-out     | LTH                     | FPLM: the peak is flattened by vast areas of swamp vegetation. MAF/MAAE: the water budget of the Massenya floodplain has inflow of 1.7 10<sup>9</sup> m<sup>3</sup> and outflow is 0.8 10<sup>9</sup> m<sup>3</sup>; the water budget of the Yaere floodplain is inflows 3.2 10<sup>9</sup> m<sup>3</sup> and outflow is 1.1 10<sup>9</sup> m<sup>3</sup> (p.52,67). |
| Phillips & Shedlock (1993) | Delaware, USA     | GW/D   | Ponds     | Comp<sub>GW</sub> | Comp<sub>GW</sub> | GDS: the hydrology of shallow seasonal ponds is strongly influenced by the adjacent groundwater-flow system (p.176). |
| Shedlock et al. (1993)  | Indiana, USA      | GW/S   | Fen       | Comp<sub>GW</sub> | CCM                    | AGR/GDS: the interior of Great Marsh are discharge zones, whereas the margins are recharge areas during wet periods. (p.152). |
| Waddington et al. (1993) | Toronto, Canada | GW/S | Swamp | CompGW | Chem FEV: saturated overland flow from permanently saturated areas created by discharging groundwater was the major storm runoff mechanism (p.37) | FEV: + |
|------------------------|----------------|------|-------|--------|----------------------------------------------------------------------------------------|-------|
| Woo & Russell (1993)   | Saskatchewan, Canada | GW/S | Prairie slough | In-out WB | AGR: prairie depressions are likely more effective for groundwater recharge than the uplands (p.205) | AGR: + |
| Woo & Winter (1993)    | Pembina, USA | SW/S | Wetland | Same LTH | FFEV:FEV/FRE: the magnitude and duration of overland flow in wetland areas are likely to be greater than in uplands because the higher degree of saturation... and gentler gradients (p.28) | FEV: + FRR: - |
| Hey et al. (1994)      | Illinois, USA | SW/S | Constructed | Same WB | AGR: seepage was very low (0-6%) as a component of outflow (p.340) | AGR: X |
| Iriz et al. (1994)     | Sweden | GW/S | Peat | Drained CCM | FPLM: Swedish rivers showed decreased peak flows after drainage because of lowered groundwater. Peat in the Hafslos catchment had different topography and special hydraulic characteristics which resulted in an increase in peak flows. The effects of peat drainage on floods were negligible in the Svartan basin. The effect of drainage depends on the groundwater level (p.657-9) | FPLM: + FPLM: - FPLM: . |
| Johansson & Seena (1994) | Sweden and Finland | GW/S | Sweden: bogs | Drained CCM | FPLM:MAF: neither peaks nor runoff differed DPFV: summer low flows were slightly higher Finland: FPLM: there was a slight increase in peaks DPFV: there was a slight increase in low flows MAF: total runoff volume increased by 3.5% (p.62-66) | FPLM: - MAF: MAF: - DPFV: - |
| Price & Maloney (1994) | S.E. Labrador, Canada | GW/S | Domed bog and fen | In-out CompGW | FEV: storm flows flooded the fen and water was quickly discharged. DPAE: the large depression and detention storage of both systems enhanced evapotranspiration losses (p.328) | FEV: + DPAE: + |
| Burt (1995)            | UK | SW/S | Peat | Multiple LTH | Flow duration curves from peat-covered basins comparatively demonstrate DPFV: minimal baseflow in summer because there is virtually no drainage from the peat (or clay) FPLM: very high flood runoff given widespread production of surface flow FVa: steep slope and therefore greater flow variability (p.25-26) | DPFV: - FPLM: + FVa: + |
| Doss (1995)            | Maine, USA | GW/D | Bog | CompGW | AGR: the volume of water that discharges through the basal peat into the mineral sediments may be low (p.224) | AGR: X |
| Khan (1995)            | Malaysia | FP | Floodplain | Same WB | AGR: groundwater recharged from the swamp will be less than from surrounding areas (p.29) | AGR: - |
| Mehg (1995)            | Botswana | FP | Floodplain | Same CCM | MAF/MAAE: the wetland was a major cause of water loss from the Bokaa catchment losing about 12 Mm3 yr-1 MAF: the wetland is recharged by river flows and loses water by evapotranspiration through the dry season (p.38) | MAF: - MAAE: + DPAE: + |
| Owen (1995)            | Wisconsin, USA | SW/S | Peat | In-out WB | AGR: wetland did not make substantial contributions to recharge FPLM: the wetland did not play an important role in attenuating flood peaks DPFV: the wetland did not make significant contributions to streamflow under low river flow conditions (p.185) | AGR: X FPLM: - DPFV: - |
| Thompson & Hollis (1995) | Nigeria | FP | Floodplain | Same WB | AGR: the wetlands play a vital role in aquifer recharge. The key is the annual wet season flooding (p.97) | AGR: = |
| Reference                      | Location                | Type       | Area          | Method       | Notes                                                                                                                                 |
|--------------------------------|--------------------------|------------|---------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Hollis (1996)                  | Senegal                  | Floodplain | Same          | WB           | AGR: the surface aquifer is recharged by the vertical percolation of floodwater (p.172)                                               |
| Gerla and Matheron (1996)      | North Dakota, USA        | Sw/D       | Wetlands      | CompGW, CCM  | WPGR/DPGR/GDS: Results show that groundwater flow into the Lake ranged from –0.030m³/day during the late winter to +0.043m³/day several times during the summer (p.914) |
| Gonthier (1996)                | Eastern Arkansas, USA    | FP         | Floodplain    | In-out       | AGR: During a significant percentage of the monthly water level measurements surface water inundating the wetland had sufficient hydraulic head to flow through the confining unit and the upper part of the alluvial aquifer to the lower part of the alluvial aquifer and away from the Black Swamp (intermediate recharge). The greater the distance from the river, the less likely the groundwater from the site will flow to the river and the more likely it will flow to the lower part of the aquifer (p.338) |
| Hunt et al. (1996)             | Southwestern Wisconsin  | FP         | Floodplain    | In-out       | GDS: Groundwater inflow rates range from 0.2-0.8 cm/day on the site with areas of higher inflows located closer to the river (p.505)       |
| Hodnett et al. (1997)          | Amazonia, Brazil         | FP         | Floodplain    | CompGW, CompGW | GDS: Floodplain water levels are controlled primarily by discharge of groundwater which maintains dry season streamflow                      |
| Matheney and Gerla (1996)      | North Dakota, USA        | Sw/D       | Wetlands      | CompGW, CCM  | AGR/GDS: although hydraulic gradients are upward over most of the year, discharge of water from the Dakota aquifer contributes less than a few tenths of a percent to the wetland water budget… the recharge-discharge function of Lunby and Stewart wetland is in a state of dynamic equilibrium (p.119) WPGR: deep penetration may occur during repeated, relatively brief periods of reversed hydraulic gradient corresponding to spring recharge and periods of above normal rainfall (p.118) |
| Walton et al. (1996)            | Eastern Arkansas, USA    | FP         | Floodplain    | In-out       | LTH: Hydrograph peaks downstream of the wetland occurred 4 to 8 days later than at the upstream gauge (p.283) FPLM: The mean reduction in peak discharge between the two gauges was about 20% (p.283) |
| Hooijer (1996)                  | Shannon, Ireland         | FP         | Callow        | CompY, CompY | FEV: The floodplains have a considerable flood control capacity; if the minimum 3500ha of callow land is flooded to an average depth of 1m, this represents a storage equivalent to one day of Shannon peak discharge (around 400m³/s)³) (p.195) |
| Hamilton et al. (1997)          | Pantanal, Brazil         | FP         | Floodplain    | WB           | MAAE: discharges of inflowing rivers is approximately equal; to the outflow from the Pantanal on an annual basis, water lost by evaporation is roughly balance by direct precipitation (p.258) |
| Logan and Rudolph (1997)        | La Plata, Argentina      | Sw/D       | Marshes       | CompGW, CHEM | AGR: vertical gradients in the marsh are generally downward throughout the year, suggesting that the Marsh is a predominantly groundwater recharge area, especially the lower lying, wetter areas (p.229) |
| Study Authors            | Location          | Type                | Method                | Groundwater Flow | Surface Water Flow | Notes                                                                 |
|--------------------------|-------------------|---------------------|-----------------------|------------------|--------------------|----------------------------------------------------------------------|
| Hayashi et al. (1998a and 1998b) | Saskatchewan, Canada | GW/D Slough In-out CHEM/WB | AGR: The vertical hydraulic gradient was downward throughout the year, leading to a total of loss of the system to groundwater of 480mm although only 2mm of groundwater flow becomes net groundwater recharge to the aquifer, the rest is transferred to the surrounding vegetated areas where it is evaporated. MAAE: evapotranspiration in the upland planted with wheat is greater than in the wetland (830mm versus 300mm). |
| Hillman (1998)            | Alberta, Canada   | FP Floodplain In/out SEH | FPHM: Flow downstream of the wetland was 6% of the peak flow upstream (0.953 m³/s downstream compared with 15 m³/s upstream of the wetland area). FEV/FTTP: the wetland greatly attenuated the flood wave in terms of volume and timing. |
| Ferrari et al. (1999)     | Aral Sea, Uzbekistan | FP Deltaic floodplain In-out WB | MAF/FPLM: The addition of wetlands in model grid boxes reduced both mean and summer peak flows. (p. 1874). |
| Genereux and Slater (1999)| Everglades, USA   | General Canal In-Out WB | AGR: between 50-90% of water entering the canal each month was seepage from the target wetland. (p. 166) |
| Gerla (1999)              | Central Minnesota, USA | GW/S Headwater wetlands CompGW CompGW GDS: On the Shingobee river, wetlands around the river provide 46.3l/s on average to a stream where flow is about 200l/s. (p. 400). |
| Hardy et al. (2000)       | Devon, England    | FP Floodplain In-Out SEH | FPLM: floodplain reduced flood peak by 7% (p.212). FPHM: floodplain reduced flood peak by 19% (p. 212). FTTP: For two events, floodplain increased lag by 35 and 4 hours respectively (p.212). |
| Raisin et al. (1999)      | North-east Victoria, Australia | GW/S Reed swamp In-Out WB | DPFV: although flow into the wetland was negligible over extended periods, a baseline discharge from the wetland of around 0.65 ML/day was usually measured (p. 139). GDS: During the relatively dry detailed study period the groundwater flow component comprised an estimated 97% of the surface flow leaving the wetland (p. 139). |
| Spieksma (1999)           | Lower Saxony, Germany | SW/S Bog Drained/Pair LTH | DPFV: The previous data show that most water yield is produced during winter and that perennial storage is not available to sustain flow during dry periods... rewetted raised bogs are not very effective as long term storage areas and regulators of stream flow. DPAE: Water yields during summer were usually zero or very low, since most of the summer rainfall was lost through evaporation and transpiration. GDS/AGR: groundwater flow is not a typical feature of raised peat bogs. |
| Taylor and Howard (1999)  | Uganda            | GW/S Swamp-filled drainage channels Pair LTH | WPGR: Between 1988-1993, recharge occurred only in one year and was dependent upon years of exceptionally heavy rainfall (p. 46). MAF: Surface runoff in the Aroca catchment (with wetlands) is 3mm compared to 34mm in the Nyabesheki catchment (without) (p. 67). MAAE: Isotopic data show that river waters have been subjected to significantly less evaporation than wetland waters... surface water have a prolonged residency, which leads to greater exposure to evaporation (p. 66). |
| Location    | Country, USA | SW/D Drainage Channel | In/out | CHEM, WB | AGR/GDS: Estimated net groundwater fluxes were almost entirely negative values indicating that groundwater recharge commonly exceeded groundwater discharge; approximately 31% of the water supplied provides recharge to the underlying aquifer system. Groundwater discharge was negligible in comparison (2.8%) (p. 510) | AGR: = GDS: = |
|-------------|--------------|------------------------|--------|----------|--------------------------------------------------------------------------------|------------------|
| Everglades  |             |                        |        |          | McCartney (2000) Zimbabwe GW/S Dамбар In/out WB FEV: “...saturation overland flow, arising within the area of the dambo, is the principal mechanism of storm runoff generation” | FEV: +            |
| Florida, USA|             | FP Pond cypress wetlands | In/out | WB       | Riekirk and Korhnak (2000) AGR: Annual deep seepage into the underlying aquifer was 17 cm yr⁻¹ for two wetlands, but in wetland N, underlain by a thick layer of blue clay this was only one cm yr⁻¹ (p. 452). | AGR: =            |
| Okavango, Botswana | FP Swamp | CompGW CompSW |        |          | Wolski (2002) Okavango, Botswana AGR: “…shallow groundwater is recharged by infiltration and lateral flow from the floodplain. A difference in flood level of 0.6 m was accompanied by a difference in groundwater storage, expressed in terms of groundwater level of at least 3 m.” | AGR: +            |