Pergamon

Wat. Sci. Tech. Vol. 32, No. 5-6, pp. 45–53, 1995.

0273–1223/95 $9·50 + 0·00

0273-1223(95)00645-1

WATER RESOURCES ASSESSMENT AS THE BASIC TOOL FOR SUSTAINABLE AND ENVIRONMENTALLY SOUND RIVER BASIN MANAGEMENT

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ABSTRACT

This paper deals with the methodology used for conducting a water resources assessment as the core component of water resources master plans. It is basically a quantitative and qualitative water resources balance (WRB) and an essential element of any short or long-term planning of sustainable and environmentally sound river basin development and management. The use of a water resources management balance instead of the water resources balance (water budget) that includes the water withdrawals and discharges in the balance equation should be favoured in water resources assessment.

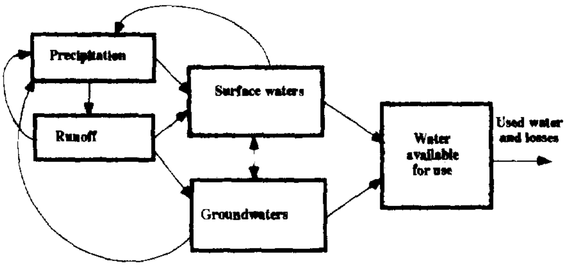
By using a water resource management balance, the multiple use of a given volume of water is accounted for so that it is possible to satisfy larger water demands than by using the natural water budget approach. This approach forces planners to look at a much wider scope of alternatives (reservoirs versus water recirculation and conservation for example) to meet the demands and also reinforces the role of water quality in water resources assessment.

KEYWORDS

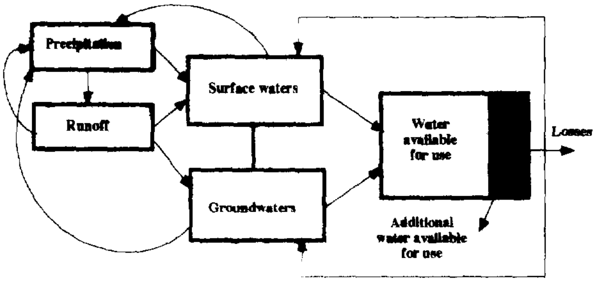
GIS; water budget; water resources assessment; water resources balance; water resources information systems.

INTRODUCTION

Water has a global role in an enormous variety of ways. It is an essential element for life on Earth, playing a major role in climate regulation and in bio-geochemical cycles. Water is also a key element in socio-economic development. As the total amount of available water resources remains more or less constant while the water demand tends to increase with the growth of population and development of industry and agriculture, it is not surprising that water is becoming a scarce resource in many regions of the world where it once used to be plentiful. Social and economic development now require people to start making major efforts to protect water and control its use and pollution. The Mar del Plata Action Plan adopted by the United Nations Water Conference in Argentina recommended the formulation of Water Resources Master Plans (WRMP) for countries and river basins. It was to provide a long-term perspective for the planning and management of available water resources (IHP-UNESCO 1985).



WATER BALANCE - WATER BUDGET APPROACH



WATER RESOURCES BALANCE APPROACH

Figure 1. Differences between the water balance and water resources management balance approaches.

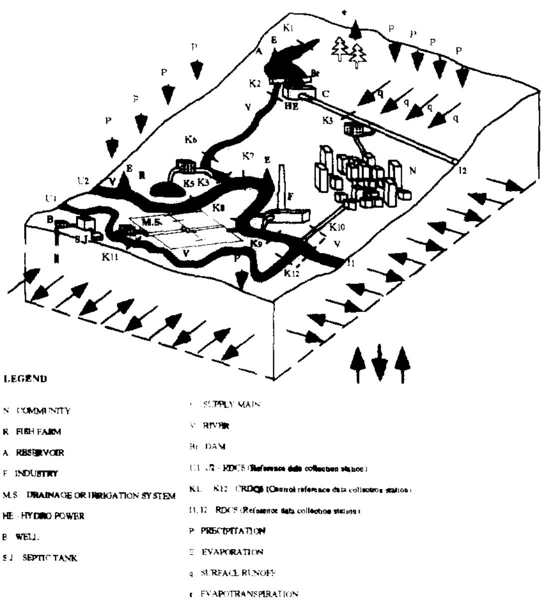


Figure 2. Schematic representation of a WMUA.

A difference must be made between the water balance or water budget and the water resources balance (WRB) (Miloradov, 1990). The difference between the two terms is that the second term includes the water withdrawals and discharges in the balance equations whereas the first one does not. In the computation of a water resources balance for a given area, the multiple use of a given volume of water is accounted for while this is not the case with the plain water balance. In making this difference in the evaluation it is possible to satisfy the water demands even when a natural water balance does not enable this. This approach also forces planners and management to look at a much wider scope of alternatives to meet the demand than would otherwise be the case (e.g. reservoirs versus water recirculation and conservation). This further reinforces the role of water quality in water resources assessment (Figure 1). It should be understood from the beginning that of the water quantities that can be managed and controlled, not all will be available for use since some water quantities must always remain in place to support the aquatic life and downstream users (Goodwin *et al.*, 1990). This instream use of water for all practical purposes is considered non-manageable unless reservoir storage is available and flow augmentation can be implemented.

WATER RESOURCES MANAGEMENT BALANCE EQUATION

If we assume that a *water management unit area* (WMUA) encompasses any area on the Earth's surface (Figure 2) where there is a certain amount of water inflow, be it in the form of surface or groundwaters or in any other form, and that there is a certain amount of runoff (surface, underground) or evaporation from the ground or water surfaces, or that some water is lost through the evapotranspiration of the plant cover, it is possible to define the *general quantitative water resources balance* for a fixed time interval.

$$\begin{aligned}\sum_{g=1}^{G}(\Delta V)_g &= \sum_{a=1}^{A}(\Delta V_{in})_a - \sum_{b=1}^{B}(\Delta V_{out})_b + \sum_{c=1}^{C}(\Delta V_{dis})_c \\ &\quad - \sum_{d=1}^{D}(\Delta V_w)_d - \sum_{e=1}^{E}(\Delta V_E)_e - \sum_{f=1}^{F}(\Delta V_{ET})_f\end{aligned} \tag{1}$$

where the following definitions apply:

$\sum_{g=1}^{G}(\Delta V)_g$	is the total change in the volume of water in a given WMUA over a given time interval. Subscript g refers to the total number of such water "reservoirs" in a given WMUA.
$\sum_{a=1}^{A}(\Delta V_{in})_a$	the total surface or groundwater inflow into a given WMUA over a given time interval in the form of rain, snow, runoff or water flowing from deep geological aquifers, as well as the water quantities flowing to the WMUA from the neighbouring WMUA. Subscript a refers to the total number of such inflows in a given WMUA.
$\sum_{b=1}^{B}(\Delta V_{out})_b$	the total number of water which in a given time interval flows out of a given WMUA and is lost through discharges into the deeper geological aquifers. This term includes both manageable and non-manageable quantities. Subscript b refers to a total number of such outflows in a given WMUA.
$\sum_{c=1}^{C}(\Delta V_{dis})_c$	the total amount of water which in a given time interval flows into surface water bodies in a given WMUA due to the discharges by different water users in the WMUA. This term refers to all point sources including the drainage system discharges. It is assumed that no discharges into groundwater aquifers exist. Subscript c refers to the total number of such inflows into a given WMUA.
$\sum_{d=1}^{D}(\Delta V_w)_d t$	the total amount of water which is withdrawn in a given time interval from surface water bodies or groundwater aquifers in a given WMUA by different water users in the WMUA. Subscript d refers to the total number of such withdrawal points in a given WMUA.
$\sum_{e=1}^{E}(\Delta V_E)_e$	the total amount of water lost from a given WMUA in a given time interval from surface water bodies due to direct evaporation. Subscript e refers to the total number of accounting areas in a given WMUA.
$\sum_{f=1}^{F}(\Delta V_{ET})_f$	the total amount of water which is lost from a given WMUA in a given time interval due to evapotranspiration by terrestrial and aquatic vegetation. It is assumed that all these losses occur from the groundwater pool. Subscript f refers to the total number of evapotranspiration accounting areas in a given WMUA.

As the above definitions imply, not all of the above terms can be quantified by direct observation. Since a water resources balance should be based on as much observed data as possible, it is necessary to desegregate Equation 1. The quantity and quality of surface waters is much easier to monitor and evaluate because the measuring and observation stations are easily defined, easily accessible and visible, this not being the case with groundwater resources (IWMH, 1985).

Equations 2 and 3 are obtained by applying Equation 1 to surface and groundwater resources and by taking care of the definitions and the associated assumptions given above. The distinction between surface and groundwaters in a water resources assessment is also important because in any given WMUA one of the resources may be given a priority in development over the other and track of each resource should be kept separately.

Surface waters

$$\sum_{n=1}^{N}(\Delta V_s)_n = \sum_{i=1}^{I}(\Delta V_{ins})_i - \sum_{j=1}^{J}(\Delta V_{outs})_j + \sum_{c=1}^{C}(\Delta V_{dis})_c - \sum_{k=1}^{K}(\Delta V_{ws})_k - \sum_{e=1}^{E}(\Delta V_E)_e - \sum_{l=1}^{L}(\Delta V_{inf\,s})_l + \sum_{m=1}^{M}(\Delta V_S)_m \qquad (2)$$

Given below are the terms which have not been defined so far:

$\sum_{n=1}^{N}(\Delta V_S)_n$	the total change in the volume of surface water in a given WMUA over a given time interval. Subscript n refers to the total number of such water "reservoirs" in a given WMUA.
$\sum_{i=1}^{I}(\Delta V_{ins})_i$	the total surface water inflow into a given WMUA over a given time interval in the form of rain, snow, runoff or water from precipitation, including the water quantities flowing to the surface waters in a WMUA from the neighbouring WMUA. Subscript i refers to the total number of such inflows in a given WMUA.
$\sum_{j=1}^{J}(\Delta V_{outs})_j$	the total amount of water which in a given time interval flows out of a given WMUA through surface water channels and man made water conduits. Subscript j refers to the total number of such outflows in a given WMUA.
$\sum_{k=1}^{K}(\Delta V_{ws})_k$	the total amount of water withdrawn in a given time interval from surface water bodies in a given WMUA by the different water users in the WMUA. This term refers to all the water withdrawals including those for the water transfer to different WMUA. Subscript k refers to the total number of such surface water withdrawal points in a given WMUA.
$\sum_{l=1}^{L}(\Delta V_{inf\,s})_l$	the total amount of water lost from a surface water pool in a given time interval in a given WMUA due to the infiltration into the groundwater aquifers. This term refers to surface water infiltration from surface water bodies only and does not include direct precipitation infiltration. Subscript l refers to the total number of surface water infiltration accounting areas in a given WMUA.
$\sum_{m=1}^{M}(\Delta V_S)_m$	the total amount of water discharged from the groundwater pool in a given time interval in a given WMUA through both surface and submerged springs. This terms includes deep aquifer springs. Subscript m refers to the total number of springs in a given WMUA.

The V_{outs} term in Equation 2 consists of two components: one that can be managed and controlled by human activities (construction of reservoirs, dams, storage tanks, etc.) and one which cannot be controlled or managed by man and includes those water quantities which are discharged from a given WMUA to support the instream requirements and downstream users (see Equation 3).

$$\sum_{j=1}^{J}(\Delta V_{outs})_j = \sum_{j=1}^{J}(\Delta V_{outsm})_j + \sum_{j=1}^{J}(\Delta V_{outsnm})_j \qquad (3)$$

where the terms undefined so far are:

$\sum_{j=1}^{J}(\Delta V_{outsm})_j$	the total amount of water which flows out of a given WMUA in a given time interval which can be controlled through a system of reservoirs and other kinds of storage. This amount of water is not of a stochastic nature and is released from a given WMUA in accordance with the management policies developed by man. Subscript j refers to the total number of outflows in a given WMUA.

$\sum_{j=1}^{J}\left(\Delta V_{outsnm}\right)_j$	the total amount of water which flows out of a given WMUA in a given time interval cannot be controlled by man. This amount of water is of a stochastic nature and is released from a given WMUA in accordance with the natural conditions for the requirements of instream water use such as aquatic life support and similar. Subscript j refers to the total number of outflows in a given WMUA.

Groundwaters

$$\begin{aligned}\sum_{u=1}^{U}\left(\Delta V_{nmg}\right)_u = \sum_{p=1}^{PI}\left(\Delta V_{ing}\right)_{pi} - \sum_{q=1}^{Q}\left(\Delta V_{outg}\right)_q - \sum_{r=1}^{R}\left(\Delta V_{wg}\right)_r \\ + \sum_{l=1}^{L}\left(\Delta V_{inf\,s}\right)_l - \sum_{m'=1}^{M}\left(\Delta V_{Ssa}\right)_{m'} \\ - \sum_{s=1}^{S}\left(\Delta V_{dao}\right)_s + \sum_{t=1}^{T}\left(\Delta V_{dai}\right)_t - \sum_{f=1}^{F}\left(\Delta V_{ET}\right)_f\end{aligned} \tag{4}$$

where the terms not defined so far are:

$\sum_{u=1}^{U}\left(\Delta V_{nmg}\right)_u$	the total change in the volume of water stored in groundwater aquifers in a given WMUA over a given time interval. It is assumed that these volumes cannot be directly controlled or managed, i.e. no man-made groundwater reservoirs exist. Subscript u refers to the total number of water aquifers in a given WMUA.
$\sum_{p=1}^{P}\left(\Delta V_{ing}\right)_p$	the total groundwater inflow into aquifers in a given WMUA over a given time interval. Subscript p refers to the total number of such inflows in a given WMUA.
$\sum_{q=1}^{Q}\left(\Delta V_{outg}\right)_q$	the total amount of water which flows out of aquifers in a given WMUA in a given time interval to aquifers in the neighbouring WMUA. Subscript q refers to the total number of such outflows in a given WMUA.
$\sum_{r=1}^{R}\left(\Delta V_{wg}\right)_r$	the total amount of water withdrawal in a given time interval from groundwater aquifers in a given WMUA by the different water users in the WMUA. This term refers to all the groundwater withdrawals including those for the water transfer to different WMUA. Subscript r refers to the total number of such withdrawal points in a given WMUA.
$\sum_{m'=1}^{M}\left(\Delta V_{Ssa}\right)_{m'}$	the total amount of water discharged from the shallow groundwater pool in a given time interval in a given WMUA through both surface and submerged springs. Subscript m' refers to the total number of shallow aquifer springs in a given WMUA.
$\sum_{t=1}^{T}\left(\Delta V_{dai}\right)_t$	the total amount of water gained by a given aquifer in a given WMUA in a given time interval due to infiltration from deep aquifers. Subscript t refers to the total number of aquifers in a given WMUA.

It was mentioned in the introduction that it is important to distinguish between the manageable terms in the water resources balance equation and those that can be rationally managed. In the above context management means the ability to store water when it is available in excess so that it can be used when there is a water shortage. For all practical reasons this is only possible with surface waters using man-made reservoirs. This does not mean that groundwater cannot be managed but only that the natural regime cannot easily be modified to serve man's needs. Instead of modifying the groundwater's natural regime, management efforts are usually directed toward preventing depletion and qualitative degradation of groundwater (UNESCO-UNEP, 1987).

In Equation 2 term V_{ins} can be simplified further into components that can be quantified by direct measurement and those that cannot. This yields the following set of equations:

$$\begin{aligned}\sum_{i=1}^{I}\left(\Delta V_{ins}\right)_i = \sum_{v=1}^{V}\left(\Delta V_{inp}\right)_v + \sum_{w=1}^{W}\left(\Delta V_{inr}\right)_w + \sum_{x=1}^{X}\left(\Delta V_{ina}\right)_x \\ + \sum_{y=1}^{Y}\left(\Delta V_{int}\right)_y + \sum_{y'=1}^{Y'}\left(\Delta V_{in}\right)_{y'}\end{aligned} \tag{5}$$

and

$$\sum_{w=1}^{W}(\Delta V_{inr})_w = \sum_{w=1}^{W}(K_r)_{wi}\times(P)_w \tag{6}$$

where the terms undefined so far are:

$\sum_{v=1}^{V}(\Delta V_{inp})_v$	the total amount of water entering the surface waters in a given WMUA due to direct precipitation on the surface of the water bodies in a given WMUA. Subscript v refers to the total number of precipitation accounting units.
$\sum_{w=1}^{W}(\Delta V_{inr})_w$	the total amount of water entering the surface waters in a given WMUA in a given time interval due to runoff. Subscript w refers to the total number of runoff accounting units.
K_r	the runoff coefficient for a given runoff accounting unit w.
P	the average precipitation over a given runoff accounting unit w.
$\sum_{x=1}^{X}(\Delta V_{ina})_x$	the total amount of water entering the surface waters in a given WMUA in a given time interval due to the water transfer from another WMUA. Subscript x refers to the total number of water transfers.
$\sum_{y=1}^{Y}(\Delta V_{int})_y$	the total amount of water leaving the surface waters in a given WMUA in a given time interval due to the water transfer to another WMUA. Subscript y refers to the total number of water transfers.
$\sum_{y'=1}^{Y'}(\Delta V_{in})_{y'}$	the total amount of water entering the surface waters in a given WMUA in a given time interval due to the inflows at the boundary reference data collection station (RDCS) from the territory of another WMUA. Subscript y' refers to the total number of inflow RDCS on the boundaries of the WMUA.

Because of the temporal variability of most of the terms in the above set of equations and the different planning and management temporal time scales it is necessary to study each component (surface waters and groundwaters) of the quantitative WRB over long periods of time if enough data is to be collected to compute the corresponding average and representative values. From the point of view of time, a water resources balance can be defined as daily, weekly, monthly, seasonal, annual and that of several years.

The realized water resources balance is processed based on actually measured, i.e. observed data during the preceding period of time. It can be processed and analyzed for all the mentioned time intervals depending on the periods of time for which there are available data.

The planned water resources balance is usually analyzed when developing WRMP and other water resources solutions for a WMUA or for higher hierarchical territorial units, based on the analysis of the water demand and the required training and protection of waters in a given water area.

The assumption is that the input and output water quantities of the water resources balance for a given WMUA are computed using the daily values when available, and are later processed for the weekly, monthly, seasonal and annual sums (and statistical values). Since there is a stochastic variability of the components of a water resources balance over a period of several years, they are analyzed and defined over several years using mathematical and statistics methods. The same is done when analyzing the water intake, the released quantity of water, and the transferred water but these quantities usually do not represent stationary time series, as is most often the case with the other components of a water resources balance.

QUALITATIVE WATER RESOURCES BALANCE

Equations 1 to 6 define the quantitative water resources balance for a given WMUA, and can be used for the qualitative water resources balance with the understanding that the water quality is defined for each component of the balance. If this is so, each term of the equations in the previous section is multiplied by a corresponding concentration of a given water quality parameter and in so doing, a mass balance per unit time can be determined for each constituent of the water quality.

Surface waters

$$\begin{aligned}\sum_{n=1}^{N}\left[(\Delta V_{S})_n \times C_n^x\right] = &\sum_{i=1}^{I}(\Delta V_{ins})_i \times C_i^x - \sum_{j=1}^{J}(\Delta V_{outs})_j \times C_j^x + \sum_{c=1}^{C}(\Delta V_{dis})_c \times C_c^x \\ &- \sum_{e=1}^{E}(\Delta V_{E})_e \times C_e^x - \sum_{k=1}^{K}(\Delta V_{ws})_k \times C_k^x \\ &- \sum_{l=1}^{L}(\Delta V_{inf\,s})_l \times C_l^x + \sum_{m=1}^{M}(\Delta V_{S})_m \times C_m^x \end{aligned} \tag{7}$$

Groundwaters

$$\begin{aligned}\sum_{u=1}^{U}(\Delta V_{nmg})_u \times C_u^x = &\sum_{p=1}^{P}(\Delta V_{ing})_p \times C_p^x - \sum_{q=1}^{Q}(\Delta V_{outg})_q \times C_q^x - \sum_{r=1}^{R}(\Delta V_{wg})_r \times C_r^x \\ &+ \sum_{l=1}^{L}(\Delta V_{inf\,s})_l \times C_l^x - \sum_{m'=1}^{M}(\Delta V_{Ssa})_{m'} \times C_{m'}^x \\ &- \sum_{s=1}^{S}(\Delta V_{dao})_s \times C_s^x + \sum_{t=1}^{T}(\Delta V_{dai})_t \times C_t^x - \sum_{f=1}^{F}(\Delta V_{ET})_f \times C_f^x \end{aligned} \tag{8}$$

The above equations do not include the terms for precipitation, evaporation and evapotranspiration, because it is assumed that the precipitation is "clean water" (although we know today that it is not quite so, e.g. acid rain), while evaporation and evapotranspiration represent a loss of clean water. What is more, it is difficult to determine the water quality for those components of a water resources balance which pertain to the input and output quantities of groundwaters, and the exchange with the deeper geological aquifers and surface water infiltration.

In Equations 7 and 8 all the concentrations of the substance identified by the superscript x are expressed in the same units while the subscript refers to the corresponding element of the quantitative water resources balance. The equations are applied for each water quality parameter of interest in succession.

INTEGRATED WATER RESOURCES BALANCE

When developing an integral water resources balance, spatial and temporal scales and the general balance equations are the starting point of the analyses. The hierarchical structure of spatial desegregation must be used for the spatial scale. Furthermore, physical characteristics of the runoff processes and the topography of the analyzed area must be considered carefully. The smallest territorial unit for the evaluation of the WRA is the water resources assessment unit area (WRAUA) which is formed by a group of water management unit areas (WMUA) defined as:

"A geographic area which encompasses the watershed of a relatively small stream or part of the watershed which represents a water resources unit suitable for WR planning. The size of the WMUA depends on the degree of hydrographic development, the topography of the terrain and the size of the country and its administrative division."

When a WMUA is part of a larger watershed, then the interdependence between the neighbouring WMUAs are accounted for in the corresponding balance equations through the corresponding V_{in} and V_{out} terms and the application of the principle of continuity (Figure 3). All the analyses are carried out from the uppermost region and along the water flow. The outflow from the upstream WMUA are at the same time the inflows to the downstream WMUA and these quantities must be equal. This means that the boundary RDCS is the same for both WMUA.

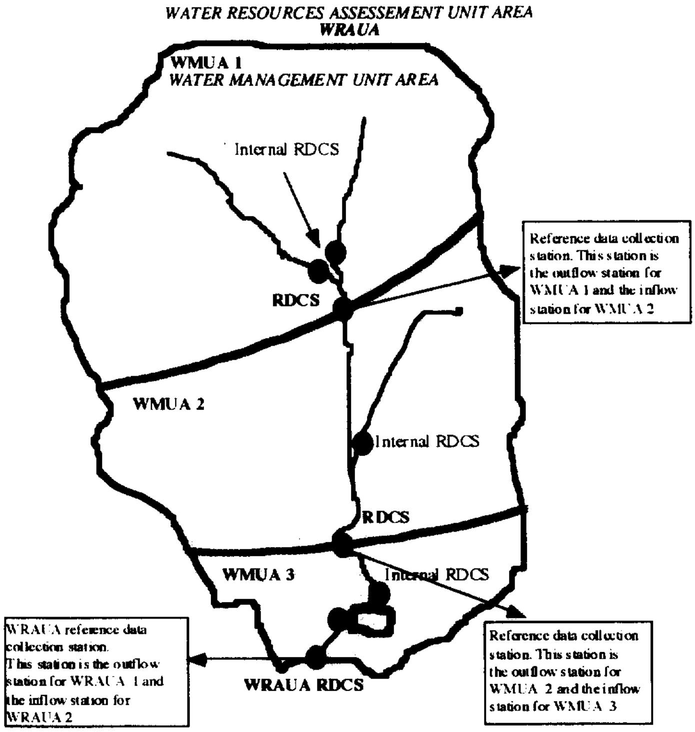


Figure 3. Integrated WRA – WMUA – principle of continuity.

Table 1. Integral water resources balance

SURFACE WATERS

Number	Name or code of WRAUA	Balance equation term	Type	Water resources, m^3							
				Jan	Feb	Mar	Apr	May	Jun	Jul	etc
1	WMUA1	$\sum_{i=1}^{I}(V_{ins})_i$	inflow								
2	WMUA1	$\sum_{c=1}^{C}(V_{dis})_c$	gain								
3	WMUA1	$\sum_{e=1}^{E}(V_E)_e$	loss								
4	WMUA1	$\sum_{k=1}^{K}(V_{ws})_k$	loss								
5	WMUA1	$\sum_{l=1}^{L}(V_{infa})_l$	loss								
6	WMUA1	$\sum_{m=1}^{M}(V_S)_m$	gain								
7	WMUA1	$\sum_{j=1}^{J}(V_{outem})_j$	loss								
8	WMUA1	$\sum_{j=1}^{J}(V_{outenm})_j$	loss								
9	WMUA1	$\sum_{v=1}^{V}(V_{inp})_v$	gain								
10	WMUA1	$\sum_{w=1}^{W}(V_{irr})_w$	loss								
11	WMUA1	$\sum_{x=1}^{X}(V_{in}a)_x$	gain								
12	WMUA1	$\sum_{y=1}^{Y}(V_n)_y$	gain								
13	WMUA1	$\sum_{y'=1}^{Y'}(V_{in})_{y'}$	gain								
14	WMUA1	$\sum_{w=1}^{W}(K_r)_w \times (P)_w$	gain								
15	WMUA1	$\sum_{j=1}^{J}(V_{outs})_j$	outflow								
	other WMUA										
	TOTAL for WRAUA										

In principle, when developing an integrated surface WRA for one or more WRAUA, track must be kept of all the "internal" terms of the balance equations (water withdrawals, water discharges, losses, etc.) while only the boundary RDCS need be considered in the balance equations (inflow and outflow) as shown in Table 1 for surface waters (a similar table is constructed for groundwater).

When conducting groundwater WRA the procedure requires that the hydrological continuity be satisfied. The only limitation which may occur is related to the application of mathematical models for the analyses and the limits they impose on the complexity of a system to be analyzed. What is usually done are the analyses for areal units which are of similar hydrogeological characteristics.

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