Senate Department for Urban Development and the Environment

02.13 Surface Runoff, Percolation, Total Runoff and Evaporation from Precipitation (2013 Edition)

Overview

The prerequisite for a water-management planning process and a management system for water resources oriented toward the principles of sustainability is that the knowledge of surface runoff and percolation, and of new groundwater formation, be as precise as possible. For this, an accounting of the components of the water balance is of special importance, especially in the Berlin area, which has only limited water resources, compared with other urban areas, and where the number of its inhabitants and their drinking and industrial water needs, and the associated sewage output, result in a structural water-management deficit.

Moreover:

- It is important for the prevention of water pollution to be able to assess the amount of surface water flowing into the local bodies of water, since the precipitation water carries a considerable pollutant load into those bodies of water with it;
- It is important for the protection of groundwater to have knowledge of the percolation capacity of the soils, since the transportation of substances from contaminated soils occurs largely via percolation water;
- It is important for conservation and landscape management to assess the water availability for vegetation from new groundwater formation and capillary water rising from the groundwater surface.

The water supplied by precipitation to an area is broken down into the various components of the water balance, depending on climatological conditions and other local characteristics. These components are evaporation, surface runoff, sub-surface runoff (percolation or new groundwater formation) and water-inventory change. The parameter which must initially be ascertained is total runoff, the sum of surface and sub-surface runoff.

According to the general water-balance equation, total runoff equals the difference between precipitation and real evaporation. In this calculation, evaporation is the decisive quantum which, under natural conditions, is determined largely by vegetation, climatic conditions and soil conditions.

In urban areas however, real evaporation is considerably different from that of the surrounding countryside. Buildings and impervious areas in cities cause evaporation to be considerably lower than in areas covered with vegetation. While the plants continually perspire through their foliage, the only water to evaporate from the surfaces of buildings and impervious areas after rainfall is that small amount which has remained on their surfaces. Thus, total runoff is considerably higher in urban areas than in vegetation-rich areas.

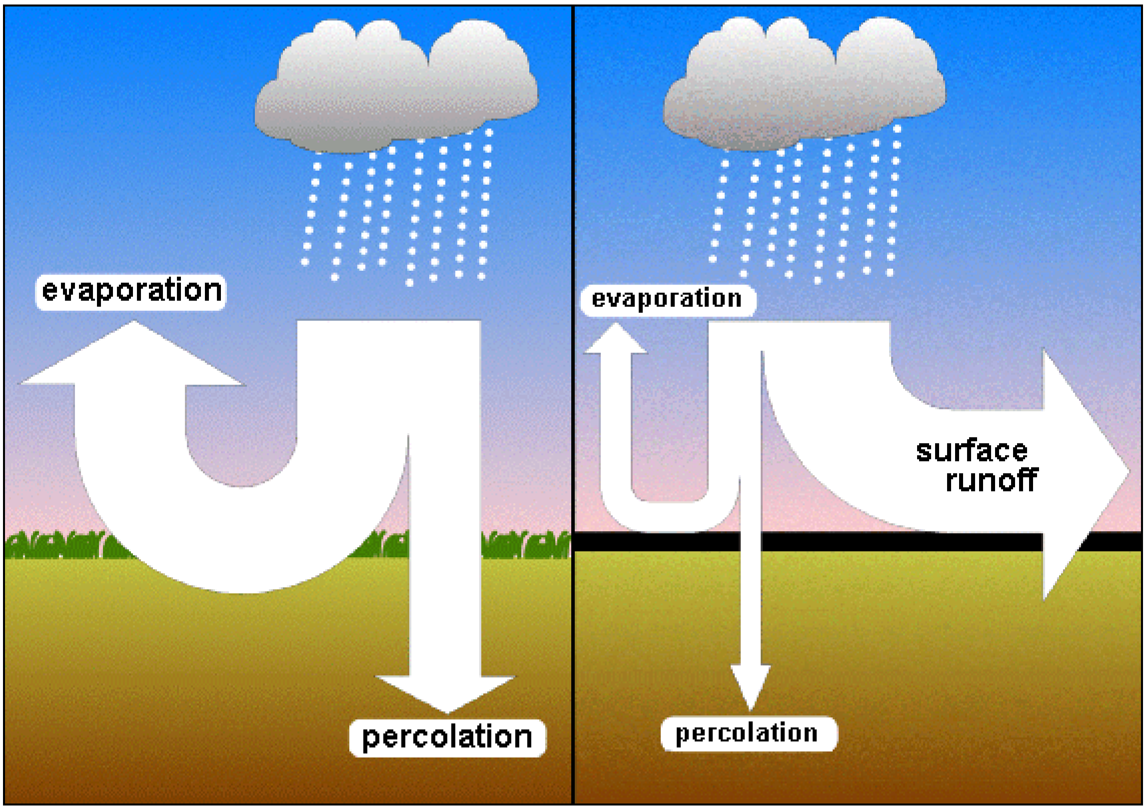


Fig.1: Water balance in vegetation areas and impervious coverage areas

Total runoff best characterizes the hydrologic conditions of catchment areas and segments. For closed catchment areas, the sum of the runoff of all segments equals the total surface and sub-surface runoff of the area, i.e., the **water supply**.

In urban areas with **impervious surfaces,** part of the total runoff flows directly into the watercourses via the appropriate inflow points, or indirectly via the sewage treatment plants – regardless of the degree of connection of these areas to the wastewater/sewage system. The rest of the runoff infiltrates the ground at the edge of the impervious areas or within the partially impervious areas, into the strata below the evaporation-affected zone, and thus recharges the groundwater. Given knowledge of the status of the expansion of the rain wastewater system, the percolation, or new groundwater formation, for these areas can therefore be ascertained by subtracting the entry of rainwater into the wastewater system from the total runoff amount.

The values on percolation and surface runoff thus ascertained are primarily of importance for water-management issues, and are also important characteristic quantities for the water balance of urban areas.

Moreover, in the context of the assessment of the efficiency of the soils for precautionary soil protection or for intervention assessment under the Conservation Law, the determination of percolation on pervious soil surfaces is of special interest. On the one hand, the differing percolation capacity of soils can be derived from this value. On the other, the effect that any planned future impervious coverage would have on the percolation capacity of a project area can be assessed in the context of the planning process.

These statements cannot be made on the basis of the values of Map 02.13.2, since the respective reference surfaces shown here are given with average values of segments containing both impervious and pervious, and both sewer-system-connected and non-connected portions.

For these reasons, in addition to Map 02.13.2, the ascertainment and representation of percolation on pervious areas has been carried out for Map **02.13.4**. It shows **percolation of precipitation on pervious surfaces**. The values shown refer only to the pervious portions of the blocks or segments.

Statistical Base

The data for the calculation of the runoff quanta for the approx. 25,000 single sections of the ISU spatial reference system were provided by the Berlin Urban and Environmental Information System (ISU). A detailed description of the data bases can be found in the extensive documentation (Gerstenberg and Goedecke, 2013).

The data on **land use** are based on the evaluation of aerial photography, borough land-use maps and additional documents for the Environmental Atlas (cf. Maps 06.01 and 06.02, as of 2011). Some twenty-two types of use have been distinguished.

The long-term average values of **precipitation** for the series of years 1961 through 1990, showing the annual average temperatures and the means for the summer semesters (May through October), were calculated from the measurements from 97 measuring stations of the Free University of Berlin and the German Meteorological Service (cf. Map 04.08, as of 1994). The data from this model were calculated for the center-point coordinates of the block segments.

For the **potential evaporation,** long-term average average values of the TURC evaporation, increased by 10 %, were used. These were calculated from observations by climate stations in the Berlin area. For the municipal area, borough-referenced values between 610 and 630 mm/yr. and between 495 and 505 mm for the summer semester were assigned.

The **degree of impervious coverage** was determined for the Environmental Atlas by evaluating ALK data (Automated Properties Map) for the built-up impervious surfaces, and by analysis of high-resolution multi-spectral satellite image data for the non-built-up impervious surfaces. The method was developed in collaboration with the Technical University of Berlin, Humboldt University of Berlin and the company Digital Services for the 2007 edition of the sealing card and used again for the 2012 edition with current data. The data initially did **not** include roadways (cf. Map 01.02, as of 2012). The data base distinguishes between the **built-up impervious** area (roof surfaces) and the **non-built-up impervious** area (parking lots, walkways etc.). For the non-built-up impervious area, the proportions of various **surface-cover types** was also an important factor. The surface-cover types were grouped into four surface-cover classes (cf. Tab. 2), and specifically ascertained for individual structural types on test areas in the terrain, and then referenced to all block segments of the same structural type.

Details on the impervious coverage degree of **roadway areas** were taken from statistics on roadways and their pavements from the Senate Building Department. The surface-cover types listed there were grouped into the above-mentioned surface-cover classes. Since these statistics only exist at the borough level, the impervious coverage degree and surface-cover class distributions were assigned generally to all areas of each borough.

The **soil-scientific data** on the usable field capacity of the shallow-root zone (0-30 cm) and the usable field capacity of the deep-root zone (0-150 cm) were derived from the Berlin Soil Association Map (cf. Map 01.01, as of 2013) in the context of an expert report (Aey 1993).

For the determination of the **depths to water table**, a digital terrain model with a 5 m grid width was used (cf. Map 01.08, as of 2010). Parallel to that, a model of the height of the groundwater surface was compiled from measurements at observation pipes of the State Groundwater Service and by the Berlin Water Utility obtained of May 2009. The depth-to-the-water-table data used for the calculation of the runoff were then calculated for the center-point coordinates of the block segments from the difference model between the altitude model and the groundwater height model (cf. Map 02.07, as of 2010) for the block segments.

The **section size** is used for the calculation of runoff volumes. The size of each block segment (without roadway areas) is available from the ISU. In addition, the estimated surface area of the roadway surface, referenced to each single block segment, was indicated. For this purpose, available data on the area of roadways at the level of the statistical area were weighted for surface area and calculated for the segments.

The data on the **wastewater/sewage system** were obtained from the Map Disposal of Rainwater and Sewage (cf. Map 02.09, SenStadt 2012), which shows the situation as of the beginning of 2012. The criterion was the existence of sewage lines for rainwater in the adjacent streets. The data is therefore initially independent of actual inflow of rainwater. The map only states whether the block is connected to the wastewater/sewage system at all. It is to be assumed that some highly impervious areas (mostly industrial and commercial areas) pass their rainwater on via the public wastewater/sewage system or private pipes, but no information is available on this.

However, the map did not yet state the extent to which the water derived from the built-up or impervious areas is actually passed on. For this purpose, special investigations have been necessary. For an estimate of the **actual degree of connection to the wastewater/sewage system**, one new data source had become available since the first application of the model to Berlin (SenStadtUmTech 1999). In the context of the restructuring of the sewage-fee schedule by the Berlin Waterworks (BWB), a property-specific survey of impervious areas was carried out, which distinguished between connected and non-connected impervious areas. Its purpose was to determine the costs of rainwater disposal, largely according to the principle of causality. These data were also recorded graphically and submitted to the Senate Department, aggregated to the data surfaces of the spatial reference system of the ISU. The evaluation of these data showed, however, that the BWB's graphic recording had not been carried out everywhere. For this reason, the original data could not be used directly for the water balance model. Based on the consideration that the degree of connection is closely related to the age and structure of the buildings, averge values were therefore determining arithmetically for each structural type from the BWB data and the map of building structures (cf. Map 06.07, as of 2011), which covers all areas, and assigned to all single blocks connected to the wastewater/sewage system. The results are summarized in Tab. 1. A comparison of the values with those ascertained by Bach (1997) yielded good agreement. Only in the case of green and open areas with little or no built-up component, the degrees of connection of the non-built-up impervious surfaces differ strongly from the values determined by Bach.

Tab. 1: Effective Degree of Connection of Sealed Areas to the Sewage System (Sewage Service Level) for Berlin Urban Structural Types, calculated from data obtained by the Berlin waterworks (BWB data as of: 2003, data processing: 2012)						
Section type		Degree of connection to sewage system built-up impervious areas	No. of data sets	Degree of connection to sewage system non-built-up impervious areas	No. of data sets	Degree of connection to sewage system impervious street areas (Bach1997)
1	Dense block development, closed rear courtyards (1870s-1918), 5-6 storey	98	174	75	174	94
2	Closed block development, rear courtyards (1870s-1918), 5-storey	95	1052	70	1049	94
3	Closed and semi-open block development, decorative and garden courtyards (1870s-1918), 4-storey	85	502	55	497	91
6	Mixed development, semi-open and open shed courtyards, 2-4-storey	75	110	54	109	91
7	De-cored block development, post-war gap closures	94	421	65	421	93
8	Heterogeneous inner-city mixed development, post-war gap closures	94	49	75	49	92
9	Large estates with tower high-rise buildings (1960s-1980), 4-11 storey	95	607	64	601	92
10	Block-edge development with large quadrangles (1920-1940s), 3-5 storey	93	579	46	569	87
11	Free row development, landscaped residential greenery (1950-'70s), 3-6 storey	86	796	50	782	89
12	Old schools (built before 1945)	87	145	66	143	88
13	New schools (built after 1945)	90	317	68	316	88
16	Sports facilities, uncovered	68	305	51	319	81
17	Sports facilities, covered	99	28	83	26	81
21	Village-like mixed development	49	85	46	84	77
22	Row houses and duplexes with yards	49	563	41	543	77
23	Detached single-family homes with yards	38	3167	30	3052	77
24	Villas and town villas with park-like gardens (mostly 1870s-1945)	56	583	45	571	67
25	Densification in single-family home areas, mixed development with yards and semi-private greening (1870s to present)	60	323	38	323	70
27	Cemeteries	63	131	56	114	81
29	Core area	94	223	84	207	98
30	Commercial and industrial area, large-scale retail, sparse development	76	743	70	746	89
31	Commercial and industrial area, large-scale retail, dense development	86	134	80	131	92
32	Utilities areas	82	75	78	71	89
33	Non-residential mixed use area, sparse development	73	132	62	132	89
36	Tree nurseries/ horticulture	55	41	59	38	81
37	Allotment gardens	59	246	54	264	81
38	Non-residential mixed use area, dense development	86	16	82	16	92
41	Security and order	82	59	75	56	88
43	Administrative	88	134	77	130	88
44	Universities and research	82	80	66	76	89
45	Culture	89	59	70	61	88
46	Hospitals	73	96	61	95	89
47	Children's day care centers	89	208	48	203	89
49	Churches	76	101	57	93	89
51	Other youth facilities	64	41	49	38	89
53	Parks/ green spaces	71	414	60	534	81
54	City squares/ promenades	84	38	72	45	81
55	Forests	0	170	0	203	0
56	Agriculture	0	31	0	35	0
57	Fallows	71	171	67	202	81
58	Camping grounds	99	4	52	2	81
59	Weekend cottages and allotment-garden-type areas	70	62	67	54	77
60	Other and miscellaneous public facilities/ special use areas	81	93	69	94	89
72	Parallel row buildings with architectural green strips (1920-1930s), 3-5 storey	80	355	46	344	87
73	Rental-flat buildings of the 1990s and later (1990 to present)	76	183	55	158	90
91	Parking lots	70	71	68	87	95
92	Railway stations and railway grounds, without tracks	86	23	78	25	95
93	Airports	99	11	92	36	95
94	Other traffic area (e.g., traffic islands, etc.)	84	65	66	99	95
99	Railroad tracks	73	91	70	106	95
100	Bodies of water	0	69	0	130	0

Tab. 1: Effective degree of connection of impervious areas to the wastewater/sewage system (sewage service level) for Berlin urban structural types

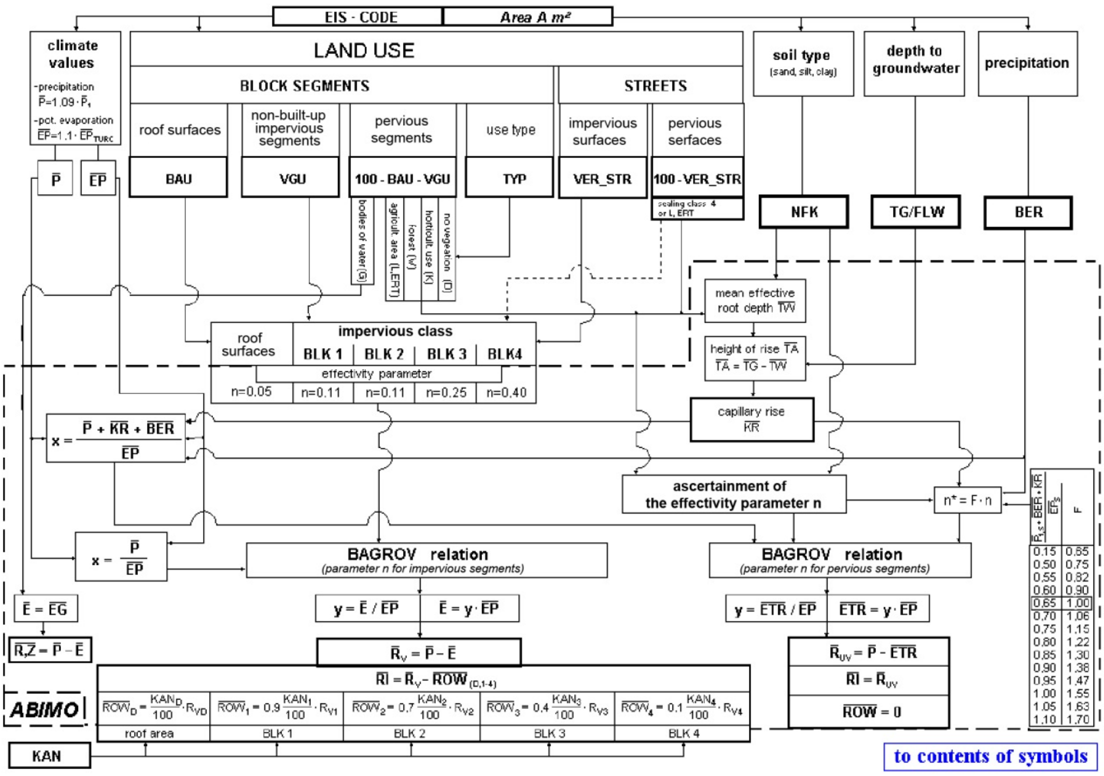
For the determination of percolation without consideration for impervious coverage (Map 02.13.4), the input data were changed by setting the impervious coverage level to zero for all sections, and hence effectively not considering it. The surface area of roadways was also set to zero, so that the resulting values refer only to the pervious surfaces of the blocks.

Methodology

In the middle of the '90s', a model for calculating the most important quanta of the water balance was developed, programmed and used in cooperation with the Berlin office of the Federal Institute of Hydrology. The approx. 25 required basic data or input parameters could be provided by the Urban and Environmental Information System (ISU) for each of the approx. 25,000 single sections. This model has been improved (ABIMO 3) and applied again with updated data.

The runoff model ABIMO developed by Glugla has been created on the basis of models developed as early as the '70s for the calculation of groundwater supply, and been expanded to include modules which take into account the special situation of urban areas. This expansion was supported by an expert report by the Institute for Ecology (soil science) of the Berlin University of Technology, and a master's thesis at the Department of Geography at the Free University of Berlin. The arithmetic implementation carried out by an external software company in addition adapted it to the specific data situation of Berlin.

The calculation method first of all ascertains the actual evaporation, in order to calculate total runoff (precipitation minus evaporation). In the second work stage, the surface runoff is determined as a share of total runoff. The difference between total runoff and surface runoff then constitutes the percolation. Fig. 2. conveys an impression of the complexity of this procedure.



Average annual values (mm/a)

$\overline{P}_1$	precipitation (1 m above the ground)
$\overline{P}$	precipitation at the soil surface
$\overline{KR}$	capillary rise from ground water near surface
$\overline{EP}$	potential evaporation *($EP = 1.1*EP_{TURC}$)*

$\overline{ETR}$	real evapo-transpiration of vegetation covered land areas
$\overline{EG}$	evaporation from bodies of water
$\overline{E}$	real evaporation of impervious areas and areas without vegetation (and from the surfaces of bodies of water)
$\overline{BER}$	amount of precipitation water
$\overline{Z} = \overline{P} - \left(\overline{E}, \overline{ETR}, \overline{EG}\right)$ $\left(\overline{E}, \overline{ETR}, \overline{EG}\right) \succ \overline{P}$	depletion of ground and surface water
$\overline{R}_v$	total runoff (impervious area)
$\overline{R}_{uv}$	total runoff (pervious area)
$\overline{ROW}$	rainwater and/or meltwater runoff from impervious area into the sewer system (or stream)
$\overline{RI}$	infiltration into the soil (below the zone influenced by evaporation)

Impervious areas (in %)

BAU	roof surface
VGU	courtyard and parking areas (non-built-up impervious areas)
VER_STR	streets
BLK 1, ..., 4	Impervious-coverage class of non-built-up impervious area
KAN	percentage of impervious areas connected to the rainwater drainage system

Land use of pervious areas

L	agricultural land use (incl. pastures)
W	forest land use (assuming of an even distribution of stocks with respect of age)
K	horticultural land use (program intern: BER = 75 mm/a)
D	area without vegetation
G	area of surface waters

Soil type

NFK	useable field-moisture capacity (moisture by volume [vol%] of field-moisture capacity minus vol% of permanent wilting point)
S, U, L, T	indication of soil type (sands, silts, clays;
N, H	low bog, high bog) for the determination of capillary rise

Depth to groundwater and capillary rise

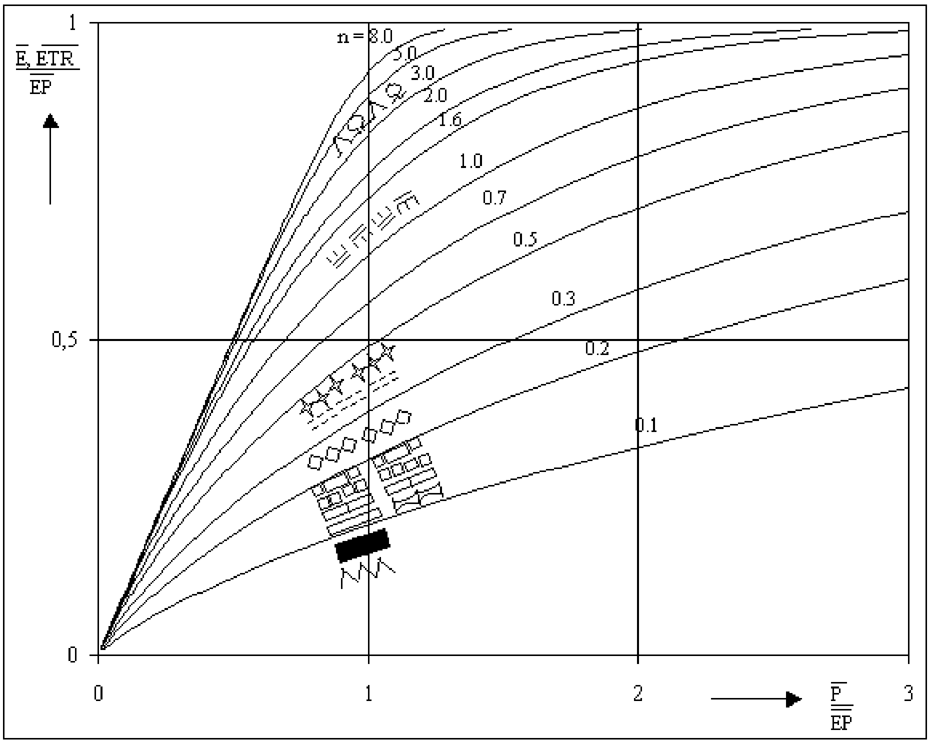
TG	depth to the water table (value in m – FLW) for the determination of KR
TA	height of rise (m), TA = TG - TW
TW	mean effective root depth (m)

Fig.2: Flow chart of the ABIMO model (from Bach 1997, modified)

Total Runoff

Total runoff s calculated from the difference between long-term annual average precipitation values and real evaporation. **Real evaporation** as it is actually encountered, as an average, at sites and in areas, is calculated from the most important quanta precipitation and **potential evaporation**, and the average storage qualities of the evaporating areas. Given sufficient moisture input into the evaporation area, the real evaporation value will approach that of the potential evaporation. The real evaporation is additionally modified by the storage qualities of the evaporation area. A higher storage effect (e.g. greater binding capacity of the soil and greater perracination depth) causes greater evaporation.

The connection shown between the average value of real evaporation over several years on the one hand and precipitation, and potential evaporation and evaporation effectivity of the site on the other fulfils the Bagrov relation (cf. Glugla et al. 1971, Glugla et al. 1976, Bamberg et al. 1981 and Fig.3). The Bagrov relation is based on the evaluation of long-term lysimetre tests, and describes the nonlinear relationship between precipitation and evaporation in dependence on site characteristics. With the Bagrov relation, the climate quanta precipitation P and potential evaporation EP (P/EP ratio), and the effectivity parameter n, and hence the real-evaporation/ potential-evaporation ratio (ER/EP) and the real evaporation ER for sites and areas without groundwater influence can be ascertained. The Bagrov method is also used in modified form to calculate the groundwater-influenced evaporation, by adding the average capillary water rise from the groundwater to the precipitation.



- sandy soil, forestry use
- sandy soil, agricultural use
- vegetation-free sandy soil
- grass pavers
- Bemburg mosaic paving
- artificial stone plates with mosaic paving (sidewalk)
- mosaic paving (sidewalk)
- concrete grass pavers (20% of area is joints, filled with sand)
- concrete surface
- concrete interlocking pavement
- asphalt (roadway)
- roof areas

Long-term mean average values of:

$\overline{E}$, $\overline{ETR}$	actual evaporation or evapotranspiration
$\overline{EP}$	potential evaporation (1.1 * TURC evaporation)
$\overline{P}$	on-grade precipitation ground
n	effectiveness parameter

Note:

$\overline{P}$ is increased by:

$\overline{KR}$	with capillary water rise from surface-proximate groundwater, and
$\overline{BER}$	with rainfall

Fig.3: Representation of the Bagrov equation for select values of the parameter n, and dependence of this parameter upon land use and soil type (from Glugla et al. 1995)

With increased precipitation P, the value of real evaporation ER approaches that of potential evaporation EP i.e., the ER/EP ratio approaches the value of 1. With reduced precipitation P (P/EP approaches the value of 0), the real evaporation value approaches that of precipitation P. The intensity with which these boundary conditions are reached is determined by the storage qualities of the evaporating area (effectivity parameter n).

The storage qualities of the site are particularly determined by the use form (increasing storage effectivity in the following order: impervious area, vegetation-free surface, agricultural, horticultural/ silvicultural use) as well as soil type (increasing storage effectivity with higher binding capacity of the soil).

The measure for the storage effectivity of pervious soil is the **usable field capacity** the difference between the humidity values of the soil for field capacity (beginning of water percolation into the ground), and for the permanent wilting point (permanent drought damage to plants). Other land-use factors, such as hectare yield and types and ages of trees, modify the parameter value n. The parameter n has been quantified by evaluation of observation results from numerous domestic and foreign lysimetre stations, and water-balance investigations in river-catchment areas.

For sites and areas with near-surface groundwater, increased evaporation compared with non-groundwater-influenced conditions occurs in the evaporation-influenced soil zone, due to the capillary rise of the groundwater, depending on the depth to the water table and soil qualities. Runoff is reduced. If real evaporation exceeds precipitation, water consumption occurs and the values for runoff become negative (e.g. river and lake lowlands).

Water areas have a higher potential evaporation than land areas, because of higher heat supply (lower reflectivity of the irradiation). For the sake of approximation, the actual water evaporation is stated as equal to this increased potential evaporation.

Selective percolation, e.g. via groundwater charging facilities by the waterworks, has not been taken into account. For gardening use (allotment gardens, , weekend cottages, parks, cemeteries, tree nurseries/ horticulture and partly in residential use or public facilities/special use), a uniform approximation value was added to the precipitation to take irrigation into account (50-100 mm/yr).

Surface Runoff

After the average total runoff has been calculated as a difference between precipitation and real evaporation, **surface runoff** is determined in a second work step. Surface runoff corresponds to the total runoff on roof areas which drains into the wastewater/sewage system. Areas not connected to the sewage system thus produce no surface runoff. Non-built-up impervious areas infiltrate a part of their drainage into the sub-surface, depending on the type of surface (surface-coverage types). This Infiltration factor is dependent on the width, age and type of the seams. The non-percolating runoff is passed to the wastewater system as surface runoff - depending on the degree of connection to the system - or, if the system does not receive it, percolates into the soil at the edge of the impervious areas. Those portions of the precipitation onto roof areas not connected to the wastewater system also percolate into the soil (cf. Tab. 1). The difference between total runoff and surface runoff thus corresponds to **percolation** as a basic quantum for new groundwater formation.

For the application of the method for urban areas, the parameters n and the infiltration factors had to be determined for the various impervious paving materials. Both lysimetre tests were evaluated with different impervious-paving materials and calculations for wetting loss (cf. Wessolek/Facklam 1997). The quanta selected for the stated parameters are listed in Tab. 2. The change of these parameters due to compression and silting of the joints associated with the ageing process has been taken into account. However, due to still insufficient scientific bases, this information still involves certain uncertainties. Moreover, a different grouping of surface coverage types into surface coverage classes would be desirable from a hydrological point of view.

Imperviousness class	Type of Imperviousness	Effectivity parameter n	Infiltration factor F_i
-	Roof areas	0.05	0
1	Asphalt, concrete, paving stones with joint sealer or concrete substructure, plastic materials	0.11	0.1
2	Artificial stone and plates (edge length > 8 cm), concrete-stone composites, clinker, medium and large-sized paving stones	0.11	0.3
3	Small and mosaic paving stones (edge length < 8 cm)	0.25	0.6
4	Grass trellis stones, waterbound cover, crushed rock, grevel	0.4	0.9

Tab. 2: Effectivity Parameter n und Infiltration Factor F_i for Various Surface Imperviousness Classes

In order to provide an impression as to how the various area uses, imperviousness parameters and conditions of the wastewater/sewage system would affect the water balance, the ABIMO model was used for approx. 35 model sections with different input quantities; the results are shown in Table 3. The relationship between surface runoff, imperviousness and evaporation is decisively dependent of the extent of impervious coverage and the passage of rainwater to the wastewater system.

Tab. 3 : Relation between surface runoff, seepage and evaporation considering as example areas of various types, sealings etc.

Area description	degree of sealing in %	of which: built-up sealed area	of which: non built-up sealed area	sealing class of non build-up areas (see tab. 2): surface-cover 1 in %	surface-cover 2 in %	surface-cover 3 in %	surface-cover 4 in %	connection to sewage system yes/no	degree of connection to the sewage system of the sealed area in %: built-up sealed area	non built-up sealed area	soil (1)	surface runoff (in % of precipitation)	seepage (in % of precipitation)	evapo-ration (in % of precipitation)
Pine wood	0	0	0	0	0	0	0	0	0	0	4	0	18	82
Meadowland	0	0	0	0	0	0	0	0	0	0	4	0	34	66
Farmland	0	0	0	0	0	0	0	0	0	0	52	0	38	62
Fallow area, former railway area	7	0	7	0	0	0	100	0	0	0	57	0	25	75
Small gardens	8	5	3	0	28	6	66	1	74	20	4	1	25	73
Small gardens	8	5	3	11	28	6	55	1	100	100	4	6	24	71
Fallow area, former railway area	21	6	15	26	0	0	74	1	100	100	57	9	30	60
Parks	24	4	20	46	0	0	54	1	74	20	6	2	28	70
Small gardens	33	21	12	13	14	27	46	1	74	20	50	5	24	71
Parks	33	8	25	27	0	0	73	1	100	100	57	14	25	62
Detached homes with large garden areas	35	25	10	0	0	33	67	1	56	35	2	9	39	53
Detached homes with large garden areas	35	25	10	25	0	33	42	1	100	100	4	27	26	47
Green spaces	37	0	37	63	10	0	27	1	0	46	52	9	33	58
Day-care centers	41	29	12	26	0	32	42	1	85	74	51	23	26	51
Green spaces	42	0	42	54	21	0	25	1	0	100	57	23	22	55
Commercial	43	31	12	32	0	0	68	1	78	54	1	18	30	53
Large housing estates	52	37	15	22	42	0	36	1	88	54	1	22	26	51
City squares	53	12	41	23	4	14	59	1	74	20	50	5	38	57
Detached homes with hollow drainage-trench system	35	25	10	0	0	33	67	1	56	35	2	0	47	53
Abandoned industrial sites, meadow like vegetation	36	0	36	100	0	0	0	1	0	20	57	5	47	47
Day-care centers with hollow drainage-trench system	41	29	12	26	0	32	42	1	85	74	51	0	49	51
Commercial	48	34	14	58	7	0	35	1	100	100	4	39	22	39
Mixed area	57	38	19	57	0	11	32	1	88	83	50	38	24	39
Sports fields/ stadiums	68	33	35	35	27	0	38	1	74	20	50	9	40	51
Parking lots	78	7	71	75	10	0	15	1	100	100	4	51	19	30
Mixed area, high sealing degree	87	47	40	21	38	27	14	1	94	68	52	43	26	31
Transportation area/stations	86	48	38	36	28	23	13	1	100	93	52	60	17	22
City squares	87	5	82	65	23	12	0	1	0	84	52	50	31	20
Mixed area, densely built-up	87	58	29	31	28	27	14	1	100	100	4	69	13	18
City squares	87	5	82	65	23	12	0	1	100	100	57	59	17	24
Industrial sites	92	54	38	83	5	0	12	1	88	83	57	64	19	17
Core areas	92	56	36	45	17	24	14	1	95	83	52	60	18	22
Abandoned industrial sites, meadow like vegetation	93	13	80	78	0	0	22	1	88	83	57	51	27	23
Industrial sites	96	54	42	79	10	0	11	1	100	100	57	79	8	13
Parking lots	98	10	88	82	10	0	8	1	87	96	50a	67	16	16

Tab. 3: Relationship between surface runoff, percolation and evaporation for areas of various types, imperviousness etc. (Köppel/Deiwick 2004)

A new version of ABIMO programme was used for the present calculation. This version differs from the old one primarily in its improved parameter control in the assignment of values for the degree of connection of roof surfaces with the wastewater system.

As a result of these calculations, updated long-term average values for total runoff, evaporation, surface runoff and percolation are available for each of the 25,000 separate sections. These values have been shown classified in mm/year in these maps; the totals in cu. m./year have also been calculated and averaged. It must be taken into account that the values shown are average values covering the sections represented as uniform areas; in fact, however, they have non-homogeneous structures. The runoffs of impervious and pervious areas have been standardized to average values per block. In addition, the runoff of roadways has been attributed to the adjacent blocks. The maps do not show, for instance, how great the percolation capacity of a square meter of pervious soil is. For this purpose, another full-coverage and block-referenced calculation has therefore been carried out with changed marginal parameters, i.e., assuming completely pervious conditions. The results of this calculation are shown in Map 02.13.4.

Map Description

The map of **Total Runoff** (Map 02.13.3) shows that the total runoff for the highly impervious inner-city areas (inside the Urban-Rail Ring Line) is in the range of 350-450 mm/yr.; the values are even higher in the very dense centre-city area and in some industrial areas. Here, only about 150 mm/yr. (Map 02.13.5) evaporate, referenced to the precipitation measurements (at 1 m height), which are about 10-15 % less than ground-level precipitation. The less densely built-up areas in the outskirts of the city show runoffs of 250-350 mm/yr. Compared with the runoffs of the pervious areas on the outskirts, or in the areas surrounding Berlin, where the values are approx. 150 mm/yr., Berlin can be considered an island of greatly increased runoff. The reduction of the evaporation due to imperviousness and lack of vegetation - as shown in the map **Evaporation** (Map 02.13.5) - leads to runoff double or triple the natural runoff.

Groundwater net consumption occurs only in a few areas characterized by low precipitation and simultaneously low depth to the water table, which produces negative runoff formation values, since here, the vegetation is fed by groundwater, and can evaporate more of it than can subsequently be supplied by precipitation.

The map of **Surface Runoff** (02.13.1) shows that in the inner-city areas connected to the wastewater/sewage system, an average of about 250 mm/yr. is fed to the wastewater system. Peaks values are more than 350 mm/yr. In outlying areas connected to the wastewater/sewage system, the values are around 100 mm/yr.

The **Percolation** map (02.13.2) shows a picture that is surprising at first glance: It shows inner-city percolation from precipitation of about 120 mm/yr. - roughly the same as for woodlands. The non-densely built-up residential areas on the outskirts show considerably higher percolation capacities of 200 mm/yr.; the values for the areas with low degrees of connection to the wastewater/sewage system in fact climb to 300 mm/yr. In the residential areas with no connection to the sewage system, all the runoff percolates into the soil, averaging about 300-350 mm/yr. and reaching maximum values of over 400 mm/yr.

In conclusion, the following can be stated:

- The effect of the reduced permeability of the soil caused by the high degree of impervious coverage in the inner city is to a large extent counteracted by the effect of reduced evaporation, so that inner-city percolation capacities are higher than initially assumed, and reach almost “natural” levels.
- The extent of impervious coverage is only secondarily important for percolation capacity; of primary importance is the actual degree of connection to the wastewater/sewage system. The type of impervious coverage, i.e. the differing percolation capacity of the various surface-cover types, also plays an important role.
- The reduction of evaporation due to impervious coverage in low-density areas with simultaneously low degrees of connection to the wastewater/sewage system causes the percolation capacities in these areas to be the highest, and approximately double those of “natural” percolation.

In the Glacial Spillway area, the percolation water can percolate directly and completely to the groundwater surface, due to the permeable sands which overlay the groundwater. Here, the calculated percolation is equal to **new groundwater formation**. On the Barnim and Teltow ground-moraine plateaus however, loamy and thus poorly water-permeable layers overlay the mostly confined groundwater. Here, the deeply cut streams are fed largely by confined groundwater or via sandy and hence permeable layers in the ground moraine. Only that part of the percolation water (calculated percolation) not passed on by the tributaries can be considered true recharging of the main aquifer beneath the ground moraine. These water quantities reach the glacial spillway area as sub-surface runoff. The break-down is respectively dependent on the concrete hydrogeological conditions. A comparison of the runoffs measured and calculated shows that e.g. in the catchment area of the

Neuenhagen Mill Stream, some 35% the calculated percolation percolates sub-surface to the glacial spillway area, while the Tegel Creek passes virtually all of the runoff it receives from the percolation of its catchment area on at the surface. A map of new groundwater formation has also been developed on the basis of the percolation-water rates determined by means of the ABIMO model (Map 02.17 as of 2013).

The evaporation from **bodies of waters surfaces,** which are not shown on the map, is approx. 152 mm/yr. more than the precipitation which falls on them, so that Berlin's bodies of water lose a total of approx. 8 million cu. m. of water per year due to evaporation.

For some very highly impervious areas, no information was available as to whether the rainwater from them is passed on via the wastewater system. For this reason, runoff for these areas has been certified in the maps as percolation. However, the degree of impervious coverage and the amount of runoff makes it seem in some cases improbable that the water actually percolates into the soil. As a result, it is likely that the share of surface runoff tends to be underestimated, and that that of percolations overestimated.

With the aid of the area sizes of the reference surfaces, the **runoff volumes** could also be calculated and then totalled (cf. Tab. 4).

Tab. 4: Long-term Average Values of Runoff Formation (determined with ABIMO3.2)

	area [km²]	mm/yr.	million cu. m./yr.
Total Berlin (without bodies of water)	837		
Precipitation (measured values, uncorrected)	837	622	521
Evaporation (Precipitation – Total Runoff)	837	370	310
Total Runoff	837	252	211
Surface Runoff	837	83	69
thereof			
Combined sewage system	83	252	21
Separate sewage system	322	150	48
Percolation	837	169	142
New Groundwater Formation	837	141	118
Bodies of Water	54		
Depletion (Precipitation – Evaporation)		-152	-8

*) area-weighted

Tab. 4: Long-term average runoff formation values (determined with ABIMO3.2)

The calculations show that about 60 % of the precipitation evaporates, and thus about 200 million cu. m./year are available as total runoff. Three quarters of this percolates into the soil to the sub-surface, while one quarter is passed through the wastewater system. Although the mixed sewage system covers only about one quarter of the total area served by the wastewater/sewage systems, it accounts for a third of total surface runoff. Comparing the annual percolation quantity of approx. 140 million cu. m., which, as stated above, is not entirely fed into the groundwater, with drinking water consumption of approx. 200 million cu. m. per year, obviously yields a considerable deficit. This deficit is compensated for by surface seepage (from the Spree and Havel rivers) as well as sub-surface influx of groundwater from the surrounding countryside. The surface water is used as shore filtrate at near-shore groundwater withdrawal facilities, and for groundwater charging at the waterworks.

Considering the changes compared with the 2007 figures, the most noticeable fact is that the long-term average of total runoff and surface drainage has continued to rise, and that concurrently, percolation and new groundwater formation have dropped still further. These changes can be attributed to the further increase in impervious coverage of the soil and the expansion of the waste water network for the removal of rainwater.

The considerable increase in evaporation since the 2007 Edition is due to methodological reason: The calculations in previous editions were based on uncorrected total precipitation figures, while the current calculations are based on corrected values.

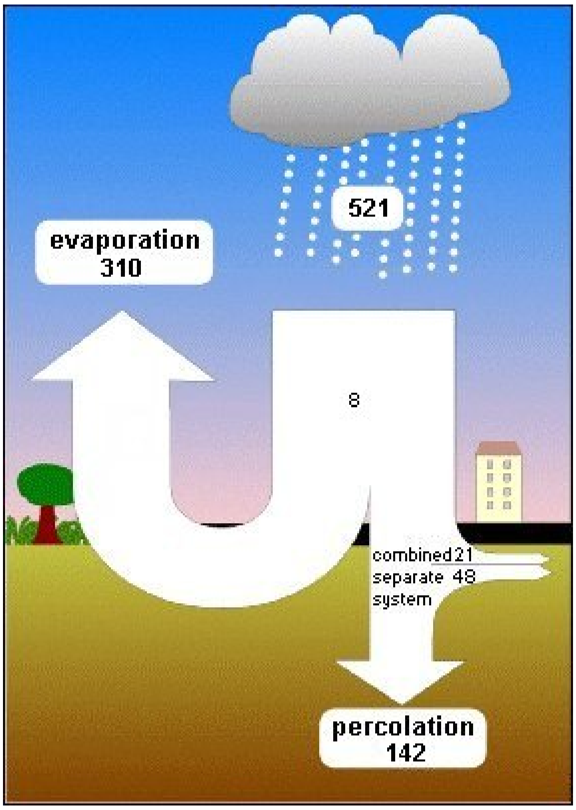


Fig.4: The Berlin water balance (long-term average values in million cu m., without bodies of water)

For each a served by the separate-wastewater system, the Information System provides data as to the tributary, body of water or body-of-water segment into which that section is drained (cf. Map 02.09.2, as of 2012) As a result, it is possible to generate balance sheets stating the amount of rainwater which each body of water has to receive, on average. About 180 bodies of water or body-of-water segments are involved.

Table 5 shows the amounts of introduction into the Berlin waters, summarized by segments. Except for those quantities which at heavy rainfall flow through the emergency outlets of the pumping stations and through the rain overflows of the wastewater network, and then also flow directly into the bodies of water, the surface runoff in the area of the mixed system is passed to the sewage treatment plants, from where they are fed into the bodies of waters after appropriate sewage-treatment, together with the treated sewage.

Tab. 5: Surface Runoff from the Separate Sewage System into Bodies of Water in Berlin, as Long-term Average Values; determined with ABIMO3.2 (data Jun. 2012; interpretation Nov. 2012)			
No.	**Surface Water Segment ('see' = lake)**	**Area (km)**	**Total (cu.m./yr.)**
110	Upper Havel to mouth Tegel Lake	2,1	0,20
120	Upper Havel (mouth Tegel Lake to Spandau watergate)	4,1	0,78
130	Tegeler See (Tegel Lake)	2,6	0,48
131	Tegeler Fließ (Tegel Creek)	5,9	0,61
132	Nordgraben (North Ditch)	11,5	1,67
133	Panke north of Verteilerbauwerk	8,1	0,85
210	Lower Havel (Spree mouth to Jungfernsee)	15,2	2,26
220	Great Wannsee	2,5	0,22
230	Kleine Wannseekette (little chain of lakes)	1,8	0,17
310	Müggelspree (incl. Great Müggel Lake and Erpe)	9,1	1,19
320	Langer See (Long Lake), Dahme, Große Krampe (lake)	7,9	0,87
330	City Spree to Britzer Zweigkanal (canal)	6,9	1,36
331	Wuhle (creek)	23,9	3,19
340	City Spree to Landwehrkanal	6,8	1,15
350	Rummelsburg Lake	10,3	2,17
351	Marzahn-Hohenschönhausener Grenzgraben (border ditch)	15,0	2,61
380	City Spree to Berlin-Spandau Shipping Canal	6,9	1,26
390	City Spree to mouth	7,0	1,34
400	Canals north of the Spree	7,7	1,60
401	Panke (Verteilerbauwerk to Nordhafen port)	19,8	3,18
500	Canals south of the Spree (Neuk. SK and Landwehrkanal)	6,5	1,51
600	Teltow Canal	66,0	9,57
610	Rudower Arm	25,4	3,28
620	Britzer Verbindungskanal	2,9	0,58
810	Grunewaldseenkette (chain of lakes)	10,8	1,64
820	Flughafensee (Airport Lake)	6,1	1,14
830	Biesdorfer Baggersee (lake)	4,7	0,55
840	Fauler See/Obersee (lakes)	1,4	0,20
850	Schäfersee (lake)	2,4	0,53
860	Groß-Glienicker See (Gross-Glienecke Lake)	0,8	0,09
900	Other small bodies of water (ponds, ...)	19,9	2,04
	Seperate sewage system (sum)	**322,2**	**48,25**
	Mixed sewage system	**83,0**	**20,98**

Tab. 5: Surface runoff from the separate wastewater/sewage system into bodies of water in Berlin, as long-term average values (data: Jun. 2012; assessment: Nov. 2012)

The ABIMO model or programme is an instrument with which simulations can also be carried out under modified circumstances. In particular, this could include an assessment of the likely changes in the water balance to be expected due to urban development projects, or of measures for the restoration of pervious situations, including the disconnection of areas from the wastewater system, to permit percolation of precipitation there. With appropriately differentiated data, the programme can also be applied on a small scale for projects at the single-lot level. Changes of the model parameters by incorporation of current findings are possible at any time.

The map **Percolation without Consideration for Impervious Coverage** (02.13.4) shows conditions which are in some cases considerably different from those shown in the Percolation map, for which impervious coverage was taken into account.

With **200-250 mm** of annual percolation, the greatly anthropogenically transformed, yet pervious, surfaces of the inner city and the industrial areas achieve the highest percolation capacities in the municipal area, followed by the predominantly sandy areas of the Glacial Spillway and the sandy parts of the plateaus, with approx. **150-200 mm**. If the sandy soils are woodlands, the average annual percolation drops to **100-150 mm**, since the trees, due to their root depth, allow considerably more water to evaporate. Due to the higher retention capacity of the loamy soils of the Teltow and Barnim plateau areas, considerably more water can also be evaporated by the vegetation there, so that only approx. **50-100 mm** percolates into the soil. In areas with near-surface groundwater, increased evaporation is caused by the capillary rise of groundwater into the evaporation-influenced soil zone, so that only an annual average of less than **50 mm** percolates into the soil. If real evaporation is higher than precipitation, net water consumption occurs, i.e. the calculated values are negative.

Certain areas have percolation capacities of more than **300 mm**; these are areas with little or no vegetation covering. Therefore only small amounts of precipitation can evaporate there; the greater share percolates into the soil.

If the data of the Map 02.13.4 are used to estimate the results of additional impervious coverage in the context of **Planning Procedures**, the following should be considered:

The percolation capacity indicated in the map is only reduced to zero by impervious coverage if the planned coverage is actually completely impervious to water (roof surfaces, asphalt) and the precipitation water of these sections is passed entirely to the wastewater system. If partially water-permeable impervious coverage is planned, or if the precipitation water runoff is to be only partially passed into the wastewater system, corresponding modification must be incorporated into the calculations with regard to the reduction of imperviousness. For **more exact calculations**, application of the ABIMO runoff model is recommended, in which simulated data for planned surface structures can be entered as input data, so that the actual state and the plan can be compared.

Excursus

Calculation of the percolation water rates on an annual and monthly basis, and forecast changes due to climate change

Water balance data calculated with the ABIMO model provide a 30 year long-term average value. However, in reality, the values fluctuate considerably on an annual basis, depending on the precipitation levels, and are also subject to fluctuations over the course of a year. In the present research project, percolation water rates were calculated with a considerably higher temporal resolution.

Project

Theresults presented below were developed in the context of the Inka BB research project of the German Federal Ministry for Education and Research (Subsidy Code 01LR0803C), Subproject 23. Inka BB is the acronym for the Berlin-Brandenburg Climate Adaptation Innovation Network (http://www.inka-bb.de/). In this research project, which was broken down into 24 subprojects, Subproject 23 addressed technologies for climate adapted water management in urban areas in the context of climate change. For this purpose, the climate scenarios developed by the project partner Potsdam Institute for Climate Impact Research (PIK) were incorporated into the various models in order to make statements on issues relevant for water management.

Statistical Base

The input data adopted comprised the land-use categories (cf. Maps 06.01 and 06.02, as of 2008), the classified degree of impervious coverage (cf. Map 01.02, as of 2007), the classified depth to groundwater (cf. Map 02.07, as of 2010), and such soil parameters as usable field capacity and Kf values from the data base of the Berlin Environmental Atlas (cf. Map 01.06, as of 2009b), for approx. 25,000 polygons. Additional soil parameters, such as porosity, were substantiated by reference to the soil associations in the Environmental Atlas (cf. Map 01.01, Map 2009b), using values from the Soil Scientific Mapping Guideline (BGR, 2005). In case of incomplete data sets, plausible assumptions were made, or data was taken from already completed DHI-WASY projects. The result was that 78 different soil types, 156 soil textures, 12 depth-to-groundwater classes and 775 land-use classeswere obtained.

The climate data used were the daily data for precipitation and potential evaporation from 11 precipitation stations in Berlin and the surrounding area. The climate data was gathered by the DWD and made available by the PIK in the context of the INKA BB research project. In order to be able to correctly represent the spatially differentiated distribution of precipitation in Berlin and the surrounding areas (cf. Map 04.08, as of 1994), the climate data were extracted by means of inverse distance weighting (a geostatistical procedure) for 19 precipitation zones. The spatial distribution of the precipitation zones is shown in Figure 5.

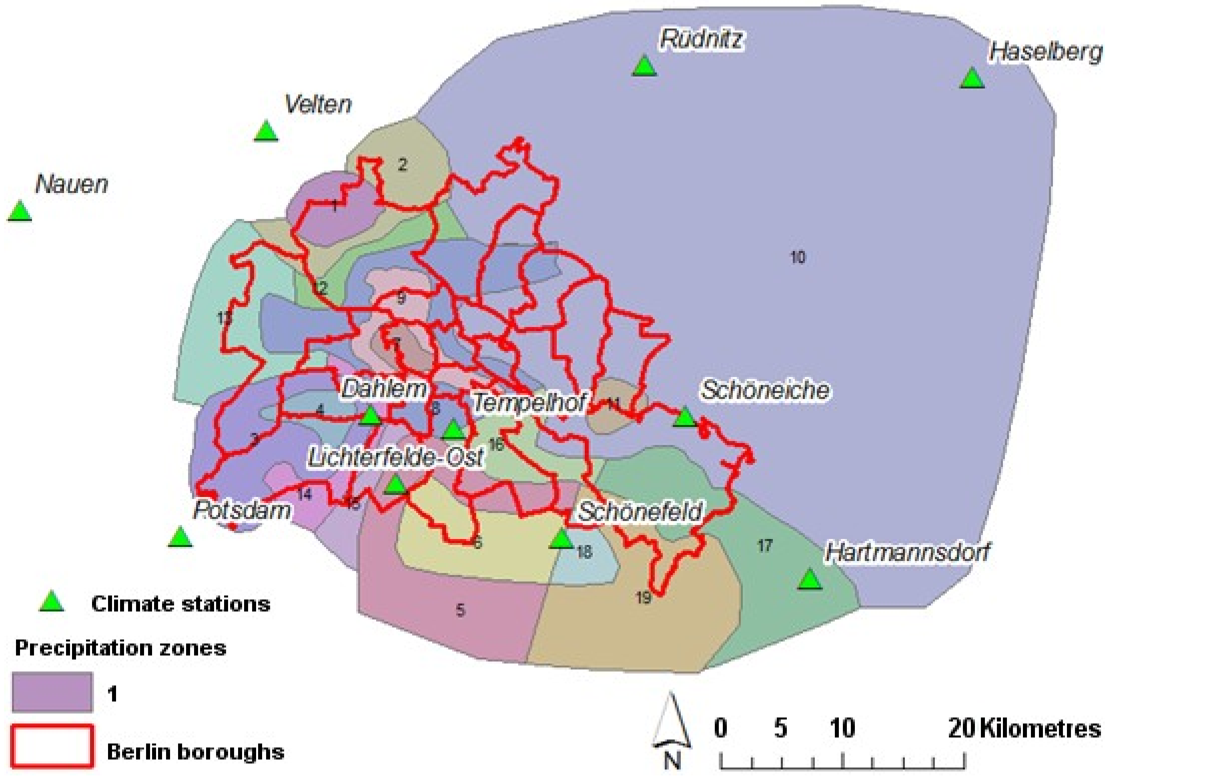


Figure 5 Distribution of the precipitation zones used in the ArcSIWA

Model Description

The results presented below are based on an ArcSIWA model designed for the entire area of the state of Berlin, including the boundaries of the intake area of the Tegel waterworks. The ArcSIWA model (Monninkhoff, 2001) is a reduced precipitation-runoff model for a one-dimensional description of runoff formation and of the soil-water balance for quasi-homogeneous area segments, with a temporal resolution of one day. The ArcSIWA accounts for interception, trench storage, infiltration and vertical dampness flow to groundwater, including new formation of groundwater and capillary rise. Thepercolation water rates calculated by the ArcSIWA correspond to the quantity of water exiting vertically from the approx. 2 m thick soil zone. A detailed representation of the ArcSIWA model built is to be presented in Sklorz & Monninkhoff (2013) sometime in 2013.

Results

Figure 6 shows the annual percolation water rates between 1961 and 1990 calculated by means of the ArcSIWA. It shows that the annual values often vary strongly, between 49 and 239 mm/a. The average value for the 30 year period is 142 mm/a, and the median value, 156 mm/a. A significant trend, e.g. due to climate, cannot be ascertained during this time period. The results are generally quite comparable with the long-term average of the percolation water rate (160 mm/a) from the ABIMO model (SenStadt, 2009c). By contrast with the values in Table 4, the stated values were ascertained by incorporating bodies of water into the average at a percolation water rate of zero. Spatial differences in the model results were particularly evident in the central part of the city, where the ArcSIWA calculated significantly lower percolation water rates. This difference is essentially due to the different approaches for impervious coverage upon which the two models are based.

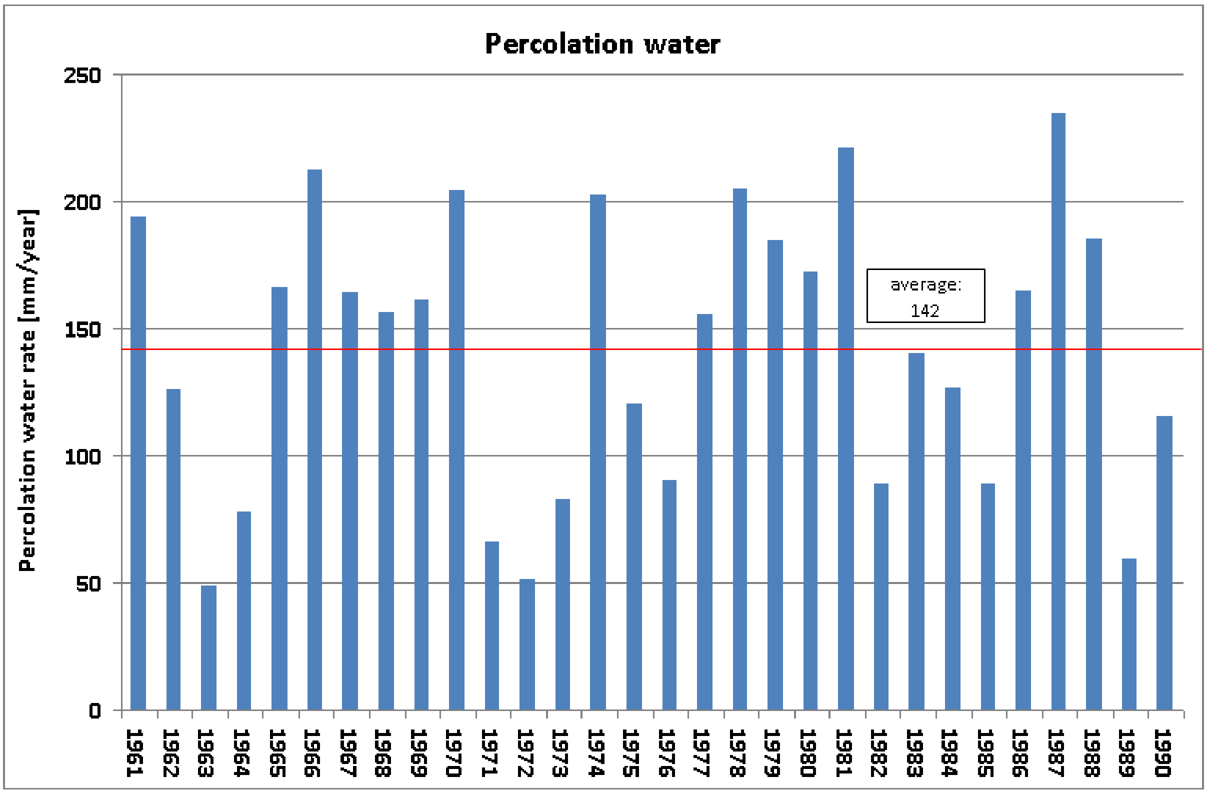


Figure 6 Annual values of percolation water rates in Berlin for the period 1961 to 1990

Figure 7 shows the long-term monthly percolation water rates for the period 1961 to 1990. It shows that the percolation water rate could vary between 1.2 and 24.5 mm per month during the course of the year. The winter months show the highest percolation water rates, while in summer, the lowest percolation water rates occur.

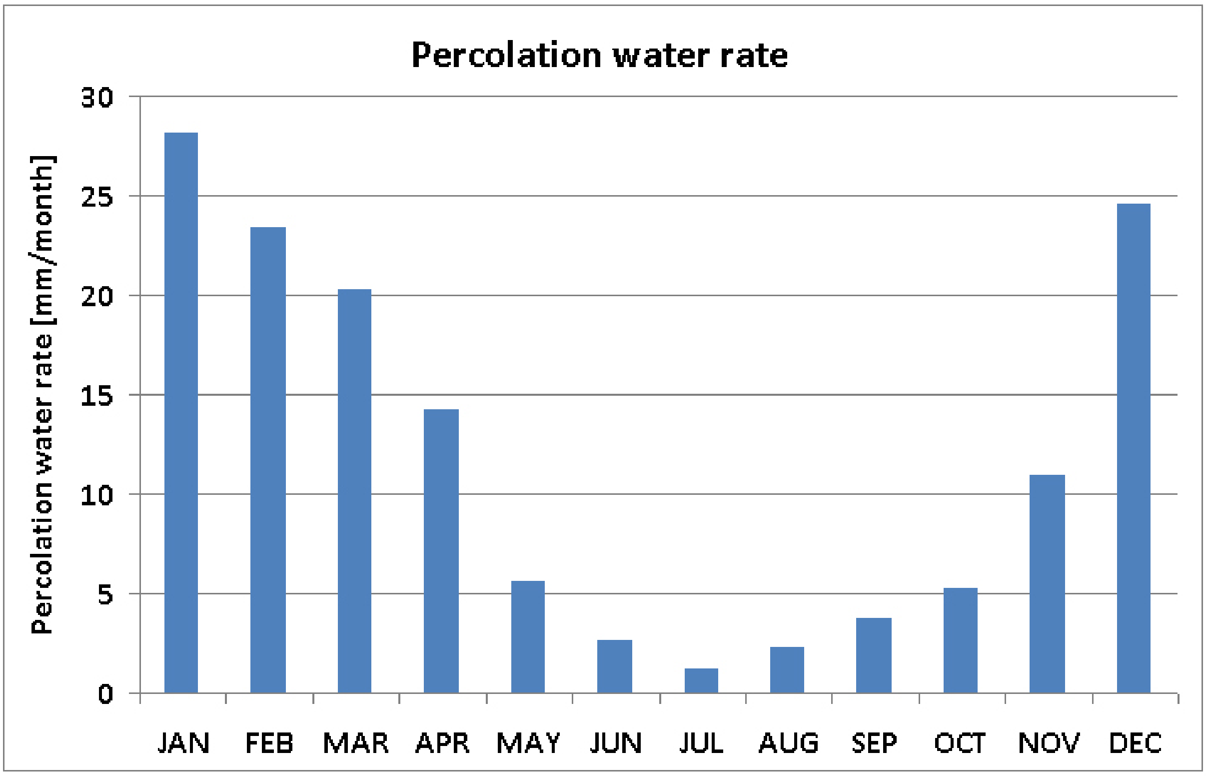


Figure 7 Long-term monthly percolation water rates for the period 1961 to 1990

The period 1961 - 1990 was used for the model calibration of the INKA BB research project, Subproject 23. Subsequently, changes of percolation water and groundwater new formation were calculated with the model based on the climate scenarios developed by the PIK. A comparison was then undertaken between the T-0 scenario (the reference scenario assuming no climate change) and the T-2 scenario (assuming a temperature increase of 2°C). The calculations show a clear reduction of groundwater new formation for the future, attributable to climate change (DHI, 2012).

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