Report
Estimating groundwater recharge rates in the southeastern Holstein region, northern Germany

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Abstract In the southeastern Holstein region, located to the east of the metropolitan zone of Hamburg, northern Germany, a groundwater investigation program was conducted from 1984 to 2000 by the State Agency for Nature and Environment (Landesamt für Natur und Umwelt, LANU) of Schleswig-Holstein, Germany, with the aim of providing long-term, ecologically acceptable groundwater management plans for the region. The focal point of the investigation comprised the determination of groundwater recharge rates. The investigation method was based on the transfer of available lysimeter results from other regions to comparable regions within the area studied. With the help of lysimeter equations, potential amounts of percolation water were calculated. The groundwater recharge rate was then determined after subtraction of the surface runoff which was calculated for the entire area. All computations were performed with a spreadsheet program. Groundwater recharge rates were calculated for two areas. One consisted of roughly determining groundwater recharge rates for the total region (1,392 km²) of southeastern Holstein. The overall goal of these investigations was to identify potential areas of water exploitation. Areas in which groundwater recharge rates are high and groundwater outflow is low are particularly suited to water exploitation, since inflow rates into deeper aquifers are high. These areas are located on the flanks of the Elbe and Stecknitz River valleys. Subsurface groundwater runoff to these lowlands would be reduced through groundwater withdrawal. However, the resulting decline in shallow groundwater tables would be so small that it would have no detrimental ecological effects. Groundwater recharge rates were also calculated for a 110-km² area in the outskirts of Hamburg (Grosshansdorf model area) which is intensively developed for water supply. These investigations showed that the amount of groundwater recharge is already being withdrawn to a large extent. Approximately 65% of the recharge rate is currently withdrawn by the waterworks in this area, thus making further increases in exploitation rates unjustifiable from an ecological point of view.

Résumé Dans le sud-est de la région d'Holstein, à l'est de l'agglomération de Hambourg (Allemagne du nord), un programme de recherches sur les eaux souterraines a été réalisé entre 1984 et 2000 par l'Agence Nationale pour la Nature et l'Environnement (Landesamt für Natur und Umwelt, LANU) du Schleswig-Holstein (Allemagne), dans le but de proposer pour la région des plans de gestion des eaux souterraines acceptables écologiquement et à long terme. Le point essentiel de ces recherches était la détermination des taux de recharge des nappes. La méthodologie mise en œuvre était basée sur le transfert des données disponibles de lysimètres obtenues dans d'autres régions à des régions comparables dans la zone d'étude. Au moyen d'équations de lysimètres, les taux potentiels de percolation ont été calculés. Le taux de recharge de la nappe a ainsi été déterminé après soustraction du ruissellement de surface qui a été calculé pour la zone d'étude dans son ensemble. Tous les calculs ont été réalisés avec un programme de feuille de calcul. Les taux de recharge des nappes ont été calculés pour deux zones. L'une constitue une détermination grossière des taux de recharge des nappes pour toute la région (1,392 km²) du sud-est de l'Holstein. Le but final de ces travaux était l'identification des zones potentielles d'exploitation des eaux souterraines. Les secteurs où les taux de recharge sont élevés et l'écoulement de sortie de la nappe est lent sont particulièrement intéressants pour l'exploitation, puisque les taux de drainage vers les aquifères plus profonds sont élevés. Ces secteurs sont localisés sur les flancs des vallées de l'Elbe et de la Stecknitz. Le ruissellement souterrain de ces basses terres pourrait être réduit par des prélèvements d'eau souterraine. Toutefois, la baisse résultante des nappes phréatiques serait si faible qu'il n'aurait aucun effet écologique préjudiciable. Les taux de recharge des nappes ont également été calculés pour une zone de 110 km² des faubourgs de Hambourg (le secteur modèle de Grosshansdorf) qui est fortement exploitée pour l'alimentation en potable (AEP). Ces travaux ont montré que le total de

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la recharge des nappes est déjà actuellement prélevé, ou presque. Environ 65% du taux de recharge est généralement prélevé par les captages de cette région, rendant ainsi des accroissements ultérieurs des taux d'exploitation injustifiables d'un point de vue écologique.

Resumen En el sudeste de la región de Holstein, que está situada al este de la zona metropolitana de Hamburgo (Alemania septentrional), se llevó a cabo un programa de investigación de las aguas subterráneas entre 1984 y el 2000, a cargo de la Agencia Estatal de Naturaleza y Medio Ambiente de Schleswig (Landesamt für Natur und Umwelt, LANU). El objetivo consistía en elaborar planes de gestión de las aguas subterráneas que fuesen ecológicamente aceptables a largo plazo. El aspecto primordial de la investigación era la determinación de las tasas de recarga a los acuíferos. El método utilizado estaba basado en la transferencia de los resultados disponibles de lisímetros en otras regiones a zonas similares en el área de estudio. Con la ayuda de las ecuaciones de los lisímetros, se calculó las tasas de precolación potencial. La tasa de recarga a las aguas subterráneas se obtenía después de restar la parte de escorrentía superficial, calculada para toda la región. Las operaciones se hicieron mediante un programa basado en hojas de cálculo. Se calculó las tasas de recarga en dos áreas distintas. La primera abarcaba el sudeste de Holstein (1,392 km^2), y pretendía obtener una aproximación. La intención global era identificar áreas sensibles a la sobreexplotación, como aquellas en las que las tasas de recarga son elevadas y la descarga de las aguas subterráneas son bajas, ya que las entradas a los acuíferos más profundos son altas. Estas zonas están situadas en las dos márgenes de los ríos Elbe y Stecknitz. La descarga subterránea a dichos valles se vería reducida a causa de la extracción de aguas subterráneas, pero el descenso producido en los acuíferos freáticos someros sería tan pequeño que no tendría consecuencias ecológicas negativas. La segunda zona, de 110 km^2, estaba localizada en las afueras de Hamburgo (área de Grosshansdorf). Se trata de una zona intensamente explotada para abastecimiento urbano. Las investigaciones mostraron que la tasa de recarga está siendo aprovechada para dicho fin; aproximadamente, un 65% de la recarga se extrae por las compañías de suministro en la zona. Desde la perspectiva ecológica, no se podría justificar un aumento del ritmo de explotación actual.

Keywords hydrological planning · percolation water · groundwater recharge · lysimeter equations · overland runoff · northern Germany

Introduction

Freshwater supply for Hamburg and surrounding areas in southeastern Holstein is based exclusively on groundwater exploitation. A broadly based hydrological investigation program was conducted to guarantee the future of

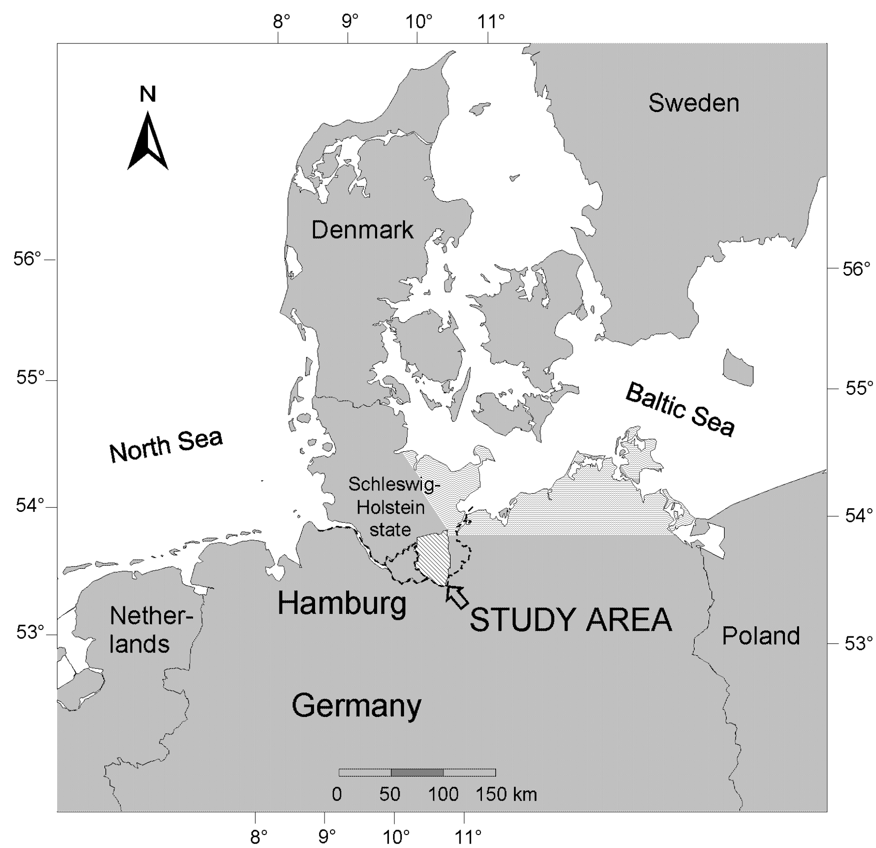

Fig. 1 Location of study area in northern Germany

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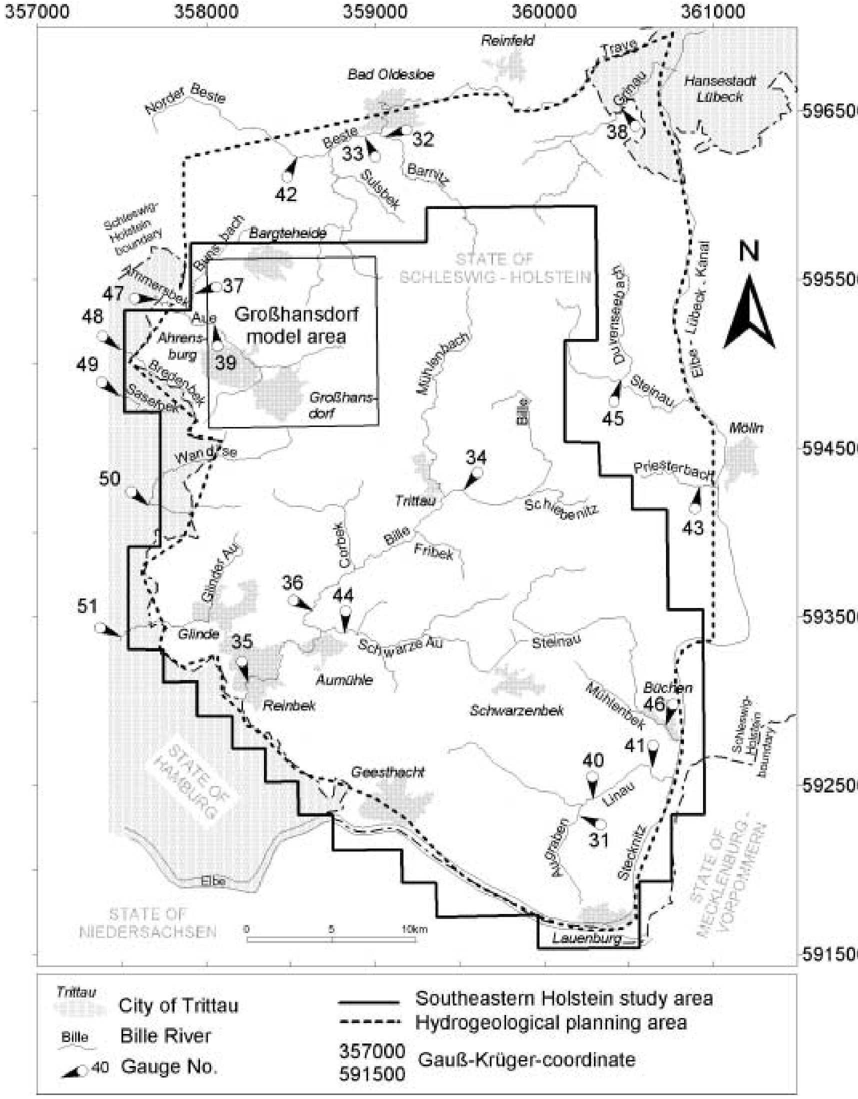

Fig. 2 Map of the southeastern Holstein study area showing relation to the hydrogeological planning area and the Grosshansdorf area

this freshwater supply. One aspect of these investigations was to determine the amount and regional distribution of available groundwater in order to facilitate long-term ecological management of the aquifers. Factors of particular importance are the avoidance of persistent drawdowns and the maintenance of good groundwater quality (Agster et al. 1999).

The southeastern Holstein hydrological planning area is located in northern Germany, to the east of the Hamburg metropolitan area (Fig. 1). The landscape is characterized by glacial features (Gripp 1964). The northern portion of the area investigated consists of young hilly moraines from the Weichsel Glacial Stage. Broad outwash plains extend westwards from the area. The southern portions of the region comprise older moraines from the Saale Glacial Stage. The landscape in this region is characterized by low rolling hills which gradually form a plateau in the vicinity of the Elbe River. These morainal landforms are referred to as geest. The southern border of the area studied is formed by the glacial valley of the Elbe.

A hydrogeological investigation program was conducted (Agster 1996) in the planning area outlined in Fig. 2, comprising a total surface area of 1,445 km^2. The thick line delineates the portion of the area studied for which a roughly discretized numerical groundwater model was developed for LANU (Hoffmann 1996a, 1996b). Groundwater flow conditions were simulated for a smaller subarea in the northwest (Grosshansdorf model area), using a finely discretized groundwater model. This model area is located in the vicinity of the small towns of Ahrensburg, Grosshansdorf and Bargteheide, and is approximately 110 km^2 in size, groundwater recharge rates for groundwater flow modeling conducted beyond the area of this study.

To meet these goals, long-term mean groundwater recharge rates and their variations were determined within the region for 1980–1991 (Otto 1997). For calculating groundwater recharge, the method developed by Josopait and Lillich (1975), as further modified by Otto (1992), was used. In accordance with these methods, the potential amount of percolation water in the study area was

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Table 1 Lysimeter equations of various authors for soil types, vegetation, and climates similar to those in the south-eastern Holstein area. Pw_{pot} Potential amount of percolation water (mm/a). *a* Gradient of straight line. *P* Precipitation (mm/a); *b* value of ordinate if P=0

Author	Soil type	Vegetation	Lysimeter equation $Pw_{pot}=a\times P-b$
Armbruster and Kohm (1976)	Sand	Fields/grassland	$Pw_{pot}=0.92\times P-324$
	Loam	Fields/grassland	$Pw_{pot}=0.86\times P-360$
Proksch (1990)	Sand	Fields	$Pw_{pot}=0.72\times P-161$
	Loam	Fields	$Pw_{pot}=0.62\times P-245$
	Sand	Grassland	$Pw_{pot}=0.92\times P-299$
	Loam	Grassland	$Pw_{pot}=0.93\times P-341$
	Sand	Deciduous forest	$Pw_{pot}=0.66\times P-199$
	Sand	Coniferous forest	$Pw_{pot}=0.58\times P-290$
Liebscher (1970)	Sand	Fields	$Pw_{pot}=0.61\times P-113$
	Loam	Fields	$Pw_{pot}=0.15\times P-28$
	Loam/sand	Fields	$Pw_{pot}=0.41\times P-12$

first determined for specified types of soils and vegetation covering the area. The amount of percolation water is defined as the proportion of precipitation water which neither runs off overland nor leaves the system through evapotranspiration. Since groundwater recharge rates represent the difference between potential amounts of percolation water and overland runoff, the regional distribution of overland runoff was determined (Otto 1997).

Methodology

Numerous lysimeters, basins filled with soil and generally covered with vegetation, are located in northern and western Europe. Precipitation and percolation-water quantities are determined on the basis of drainage-outflow amounts at the base of the lysimeter. A linear correlation exists between precipitation and percolation-water quantities and can be mathematically approximated. This investigation is based on data from numerous lysimeters interpreted by Dyck and Chardabellas (1963), which describe the long-term relation between precipitation and percolation water for certain types of soils and vegetation in humid regions. Lysimeter equations presented by other authors were, however, also taken into consideration (see below). To assess groundwater recharge rates in the study area, the potential amount of percolation water in mm/a (Pw_{pot}), as a function of precipitation (P), was determined using these equations. Here, the potential amount of percolation water, the long-term mean, is that portion of precipitation which does not evaporate. The following linear-function equations have been used to determine this mean (in mm/a) for lysimeters in sandy and clayey soils in field and grassland areas as well as in forests (Dyck and Chardabellas 1963):

- Sandy soils in fields and grassland: $Pw_{pot}=1.1\times P-433$
- Sandy soils in forests: $Pw_{pot}=1.1\times P-474$
- Clayey soils in fields and grassland: $Pw_{pot}=1.1\times P-558$
- Clayey soils in forests: $Pw_{pot}=1.1\times P-578$

The equations show that potential amounts of percolation water are highest for sandy soils in fields and grassland areas. Since evapotranspiration is low here, the infiltration capacity of this soil type is high. For clayey soils in forests, however, the amount of percolation water is lower because the effective field capacity of clayey soils is high, and stored infiltrated precipitation water thus supplies vegetation with moisture and nutrients for a longer period of time. In addition, evaporation rates in forests, especially coniferous forest areas, are particularly high.

Other authors have achieved similar results for the relation between percolation water and precipitation, with the lysimeter equations shown in Table 1, for the humid climate in northwestern Europe. With these equations, the minimum, maximum, and mean values of potential amounts of percolation water were calculated as a function of precipitation for each type of soil and land utilization. The relationships between precipitation and the amount of percolation water derived are highly characterized by the type, structure and climatic zone of the particular lysimeter. The following linear-function equations apply to the above-mentioned types of soils and land use, with the exception of lysimeters in clayey soils in forests (Otto 1999):

- Sandy soils in fields and grassland: $Pw_{pot}=0.85\times P-266$
- Sandy soils in forests: $Pw_{pot}=0.78\times P-320$
- Clayey soils in fields and grassland: $Pw_{pot}=0.68\times P-257$
- Clayey soils in forests: no data

The overall lysimeter results vary considerably due to the high variability of annual climatic trends. Additionally, even though annual means are constant, the amount of percolation water does not depend entirely on the amount of regional precipitation. For example, a warm year with many heavy rain showers in summer results in lower amounts of percolation water than does a cool year with relatively evenly distributed precipitation, even though annual total precipitation is identical. Heavy rains result in high direct runoff, i.e., a portion of precip-

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Table 2 Comparison of percolation-water values (Pw_{pot}) in the Grosshansdorf area from various lysimeter equations (water years 1980–1991)

Value	Unit	Lysimeter equations shown in Table 1	Lysimeter equations of Dyck and Chardabellas (1963)[a]
Minimum	(mm/a)	205	230
Mean	(mm/a)	299	330
Maximum	(mm/a)	465	477
Standard deviation	(mm/a)	45	49
Standard deviation	(%)	15	15

[a] In Josopait and Lillich (1975)

itation water runs off directly without percolation, whereas a cool year results in lower evaporation rates with low-intensity precipitation resulting in negligible quantities of surface runoff. Several lysimeter equation systems were tested in the Grosshansdorf model area, the results being presented in Table 2.

In calculating groundwater recharge, total runoff, consisting of surface runoff and base runoff, represents a major part of the water balance. The surface runoff (R_o) is that portion of total runoff which flows directly on, or very close to, the surface after precipitation. Subsurface or base runoff (R_u) results from the exfiltration of groundwater into receiving channels. This base flow ensures that streams do not dry up during periods of low precipitation. Interflow runoff ($R_{interflow}$) is determined mainly by drainage processes in the northern German Quaternary landscape. Total runoff (R_{tot}) was recorded by hydrological water gauges. For calculation purposes, total runoff was subdivided into an overland (surface) and an underground (base) flow, using the R_o/R_u separation method proposed by Kille (1970). This method is based on considerations by Wundt (1958), which assume that water supply during the month of lowest stream runoff (MoLQ) stems from groundwater sources. Wundt (1958) contends that the mean of monthly low-water flows corresponds to groundwater runoff:

$$R_u = \frac{\sum_{i=1}^{i=n} MoLQ_i}{n}$$

where i is number of months, and MoLQ is lowest runoff during 1 month.

Since Schleswig-Holstein lies in a region of high precipitation, it can be assumed that there are also months in which total runoff is composed of both surface runoff and interflow every day. In the Kille method, the MoLQ values for months with both types of runoff are graphically separated and removed from the calculation. Subsurface flow (R_u) is the mean of MoLQ values for an entire balance period after separation (Fig. 3). Surface runoff (R_o) is the difference between total runoff (R_{tot}) and groundwater runoff (R_u), i.e., $R_o = R_{tot} - R_u$.

Integrals for surface runoff catchment areas were determined for the entire area investigated in southeastern Holstein and entered into grid cells. If a grid cell comprised several catchment areas, runoff was determined as a percentage of catchment drainage (Fig. 4, Table 3). A finer differentiation was impracticable due to the size of the grid cells. In the Grosshansdorf model area the per-

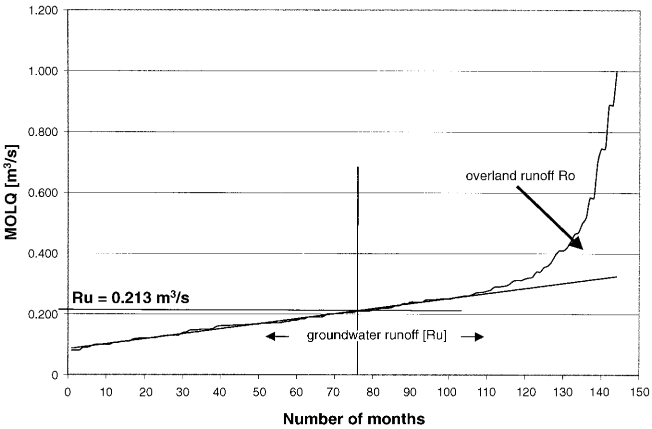

Fig. 3 Determination of underground runoff according to Kille (1970) as observed at the Hunnau River, including runoff data gathered at the Bünningstedt gauging station

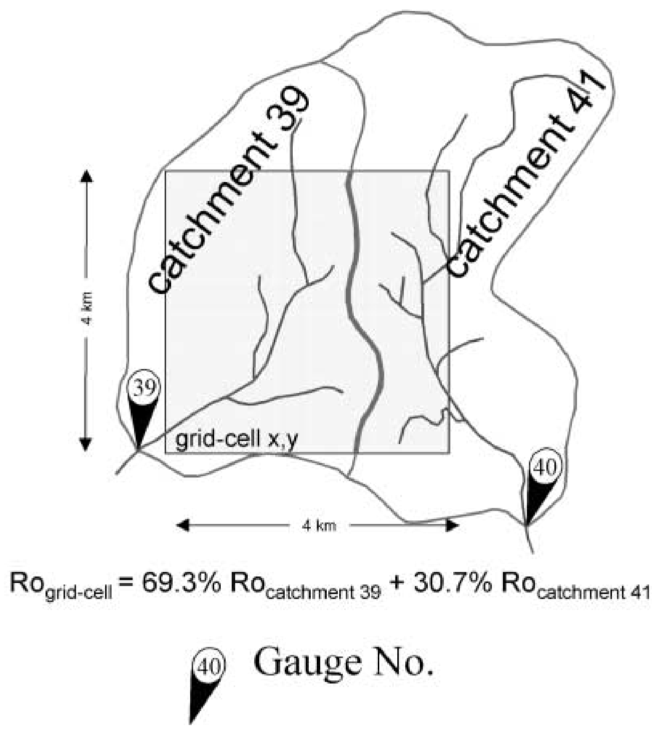

Fig. 4 Portions of surface-catchment areas in a grid cell of the study area in southeastern Holstein

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Table 3 Values for runoff components in gauge-catchment areas of southeastern Holstein (runoff data from LANU; location of gauging stations shown in Fig. 2). R_{tot} Total runoff; R_o Overland runoff; R_u Underground runoff

No.	Gauging station name	River	Area (km^2)	$R_{tot}=R_o+R_u$			R_o/R_u	R_o in % of R_{tot}
				R_{tot} (mm/a)	R_o (mm/a)	R_u (mm/a)		
31	Lütau	Augraben	34.1	91	68	23	3.0	74.7
32	Quellenthal II	Barnitz	58.8	385	277	108	2.6	71.9
33	Quellenthal	Beste	89.0	319	187	132	1.4	58.6
34	Hamfelde	Bille	66.5	299	190	109	1.7	63.5
35	Reinbek	Bille	28.1	423	34	389	0.1	8.0
36	Sachsenwaldau	Bille	156.5	250	94	156	0.6	37.6
37	Rehagen	Bunsbach	30.1	200	153	47	3.3	76.5
38	Ziegelhof	Grinau	32.5	284	224	60	3.7	78.9
39	Bünningstedt	Hunnau/Aue	64.0	186	119	67	1.8	64.0
40	Lütau	Linau	56.2	109	70	39	1.8	64.2
41	Witzeeze	Linau	15.7	235	62	173	0.4	26.4
42	Neritz	Norder Beste	48.0	363	202	161	1.3	55.6
43	Breitenfelde	Priesterbach	32.8	142	95	47	2.0	66.9
44	Aumühle	Schwarze Au	83.9	151	97	54	1.8	64.2
45	Nusse	Steinau	75.2	268	161	107	1.5	60.1
46	Pötrau	Steinau	92.3	268	122	146	0.8	45.5
47	Brügkamp (HH)	Ammersbek	13.9	665	195	470	0.4	29.3
48	Wohldorfer D. (HH)	Bredenbek	19.9	304	201	103	2.0	66.1
49	HH	Saselbek		242	155	87	1.8	64.0
50	Wilhelm-Grimm-Str.	Wandse	41.7	180	109	71	1.5	60.6
51	An der Steinbek	Glinder Au	57.0	248	167	81	2.1	67.3
	Mean values of all catchments:			267	142	125	1.6	57.3

centage of plateaus, slope areas, valleys, and sealed areas was estimated for each grid element of the model area and assigned an estimated runoff value initially based on findings by Josopait and Lillich (1975).

- $R_{plateau}=30$ mm/a
- $R_{slope,\ sealed\ areas}=100$ mm/a
- $R_{valleys}=175$ mm/a

In the next stage, these topographically oriented discharge rates were then iteratively increased until the above-mentioned values of the water gauges were reached as the runoff integral of the catchment area.

Lysimeter equations are based on the assumption that surface runoff equals zero. If surface runoff is indeed present, less percolation water is formed. In order to calculate the actual quantities of percolation water (Pw_{real}) involved, potential amounts of percolation water (Pw_{pot}) must be subtracted from surface runoff (R_o):

- $Pw_{real}=Pw_{pot}-R_o$
- Pw_{real}=real percolation water quantity
- Pw_{pot}=potential percolation water quantity
- R_o=surface runoff including interflow

Evaporation is higher on surfaces with a shallow water table (<1 m) than on surfaces with a deep water table. Therefore, the potential amount of percolation water for these areas is reduced in proportion to the rates of additional evaporation. For open-water surfaces in the area studied, evaporation was calculated according to Penman (1948).

Within the scope of the research program sponsored by LANU, covering all of southeastern Holstein, several other methods were used to quantify groundwater recharge (Bagrov and Glugla 1975; Dörhöfer and Josopait 1980; Proksch 1990; Renger and Wessolek 1990; Schroeder and Wyrwich 1990). The results are also given in Meyer and Tesmer (2000) and are compared below with the results cited in this report.

Discretization of Groundwater Model Areas and Spreadsheet Calculations

Due to the large extent of the model area (approx. 1,400 km^2), the entire area investigated in southeastern Holstein was distributed over a large grid. Groundwater recharge was determined as the long-term mean for surface integrals of 4×4 km (Fig. 5). In the Grosshansdorf model area, cell size was 500×500 m, and the region covers an area comprising 21×21 grid cells (Fig. 5).

Using lysimeter equations in combination with mean precipitation rates (P) for the area results in potential percolation water levels for each of the grid cells:

- $Pw_{pot\ cell}=A_{sand/fields,\ grassland}\times Pw_{pot\ sand/fields,\ grassland}+A_{sand/forest}\times Pw_{pot\ sand/forest}+A_{clay/fields,\ grassland}\times Pw_{pot\ clay/fields,\ grassland}+A_{clay/forest}\times Pw_{clay/forest}-A_{ld}\times E_a$

with

- Pw_{pot}=potential amount of percolation water of a cell
- $Pw_{pot\ sand/fields,\ grassland/forest}$=potential amount of percolation water on sandy soils in fields and grassland or forest
- $A_{sand/fields,\ grassland}$=percentage of sandy soils in fields and grassland

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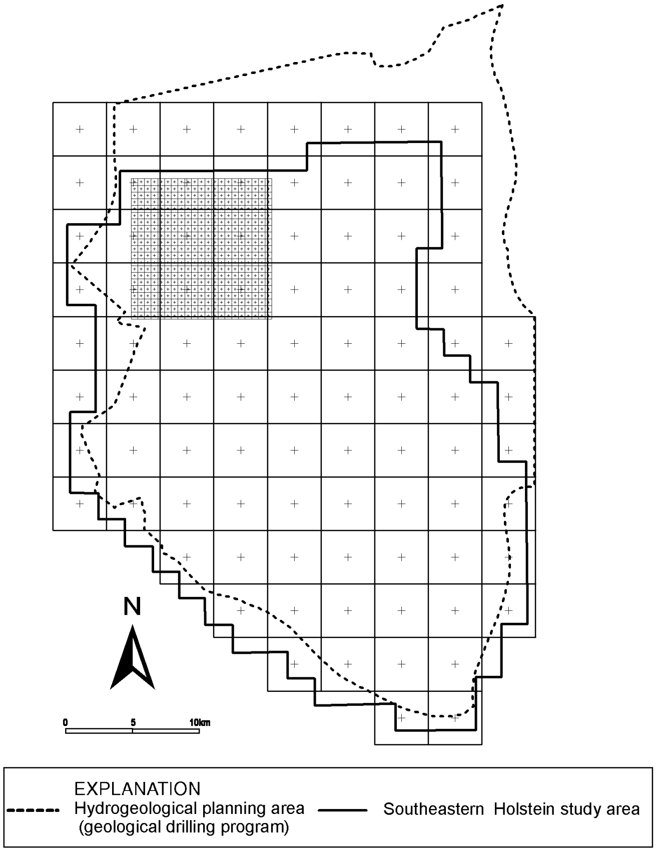


Fig. 5 Discretization of the southeastern Holstein area, showing the study-area grid-cell pattern and the pattern of grid cells in the Grosshansdorf area (*shaded area*)

- P=mean precipitation of the grid cell
- A_{ld}=percentage of areas with shallow water table
- E_a=additional evapotranspiration above shallow water table (90 mm/a)

Grid-cell-related groundwater recharge rates in the model area (GWR_{cell}) comprise the difference between potential amounts of percolation water per cell ($Pw_{pot\ cell}$) and corresponding discharge rates ($R_{o\ cell}$): $GWR_{cell}=Pw_{pot\ cell}-R_{o\ cell}$ (mm/a).

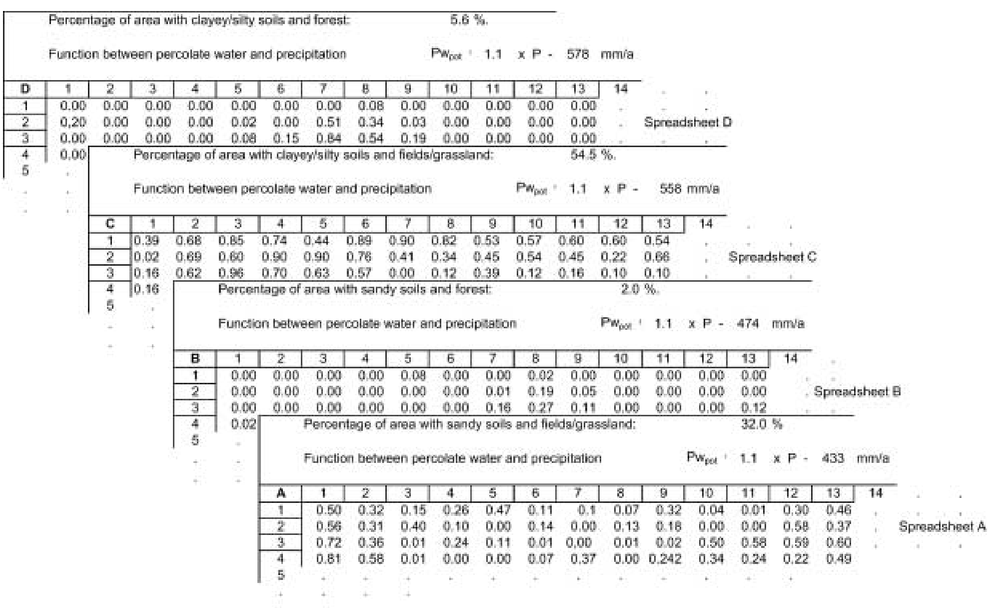
All regional data required for the determination of groundwater recharge were stored in grid cells in the worksheets of a spreadsheet file (Fig. 6). For example, the first four worksheets contain percentages of sandy soils in fields/grassland, sandy soils in forests, clayey soils in fields/grassland and clayey soils in forests, including the corresponding lysimeter equations. Together with other grid-cell-related data and precipitation distributions, the potential amount of percolation water was determined, followed by the groundwater recharge for each cell. The spreadsheet program updated all existing cell links whenever an alteration occurred in one of the individual worksheets. The calculation process is outlined in Table 4.

The spreadsheet program used in the course of these calculations is suitable only for a limited number of grid elements. For large areas and when fine discretization is required, newer technologies, such as geographic information systems (GISs), should be used (see also Meyer et al. 1998; Meyer and Tesmer 2000).

Data basis and Balance Periods

Much geological and hydrological data were required for the groundwater-recharge calculations presented here. The distribution of soil types and soil layers close to the

Fig. 6 Partial worksheets for the groundwater recharge model of the Grosshansdorf area illustrating the percentages of types of soils and vegetation cover for each grid cell (spreadsheets E–I are shown in Table 4)



Spreadsheet D

Percentage of area with clayey/silty soils and forest: 5.6 %.

Function between percolate water and precipitation Pw_{pot} = 1.1 x P - 578 mm/a

D	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	
2	0,20	0.00	0.00	0.00	0.02	0.00	0.51	0.34	0.03	0.00	0.00	0.00	0.00	
3	0.00	0.00	0.00	0.00	0.08	0.15	0.84	0.54	0.19	0.00	0.00	0.00	0.00	
4	0.00													
5														

Spreadsheet C

Percentage of area with clayey/silty soils and fields/grassland: 54.5 %.

Function between percolate water and precipitation Pw_{pot} = 1.1 x P - 558 mm/a

C	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.39	0.68	0.85	0.74	0.44	0.89	0.90	0.82	0.53	0.57	0.60	0.60	0.54	
2	0.02	0.69	0.60	0.90	0.90	0.76	0.41	0.34	0.45	0.54	0.45	0.22	0.66	
3	0.16	0.62	0.96	0.70	0.63	0.57	0.00	0.12	0.39	0.12	0.16	0.10	0.10	
4	0.16													
5														

Spreadsheet B

Percentage of area with sandy soils and forest: 2.0 %.

Function between percolate water and precipitation Pw_{pot} = 1.1 x P - 474 mm/a

B	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	
2	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.19	0.05	0.00	0.00	0.00	0.00	
3	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.27	0.11	0.00	0.00	0.00	0.12	
4	0.02													
5														

Spreadsheet A

Percentage of area with sandy soils and fields/grassland: 32.0 %

Function between percolate water and precipitation Pw_{pot} = 1.1 x P - 433 mm/a

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.50	0.32	0.15	0.26	0.47	0.11	0.1	0.07	0.32	0.04	0.01	0.30	0.46	
2	0.56	0.31	0.40	0.10	0.00	0.14	0.00	0.13	0.18	0.00	0.00	0.58	0.37	
3	0.72	0.36	0.01	0.24	0.11	0.01	0,00	0.01	0.02	0.50	0.58	0.59	0.60	
4	0.81	0.58	0.01	0.00	0.00	0.07	0.37	0.00	0.242	0.34	0.24	0.22	0.49	
5														

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Table 4 Calculation of groundwater recharge rates for each grid cell of the area studied using spreadsheet-calculation tools

Spreadsheet no.	Content of grid cell	Formula
A	Percentage of area with sandy soils and fields/grassland	$A_{sand/fields, grassland}$ Lysimeter equation
B	Percentage of area with sandy soils and forest	$A_{sand/forest}$ Lysimeter equation
C	Percentage of area with clayey/silty soils and fields/grassland	$A_{clay/fields, grassland}$ Lysimeter equation
D	Percentage of area with clayey/silty soils and forest	$A_{clay/forest}$ Lysimeter equation
E	Additional evapotranspiration E_a above shallow water table (90 mm/a), percentage A_{ld} of areas with shallow water table	$A_{ld} \times E_a$
F	Precipitation	P
G[a]	Potential amount of percolation water of a cell	$Pw_{pot\ cell}=A_{sand/fields, grassland} \times Pw_{pot\ sand/fields, grassland} + A_{sand/forest} \times Pw_{pot\ sand/forest} + A_{clay/fields, grassland} \times Pw_{pot\ clay/fields, grassland} + A_{clay/forest} \times Pw_{clay/forest} - A_{ld} \times E_a$
H	Surface runoff including interflow	R_o
I	Groundwater recharge rate	$GWR_{cell}=Pw_{pot\ cell}-R_{o\ cell}$

[a] Grid formula in spreadsheet G:
+A:C12*(A:$D$8*F:C12-A:$F$8)
+B:C12*(B:$D$8*F:C12-B:$F$8)
+C:C12*(C:$D$8*F:C12-C:$F$8)
+D:C12*(D:$D$8*F:C12-D:$F$8)-E:C32

surface were derived from geological maps. For the Grosshansdorf model area these data were based on 1:25,000-scale maps. Near-surface layers were subdivided into clayey/silty and sandy sediments. Further differentiation was limited by the amount of data available. The differentiation between sandy soils and clayey/silty soils for the total area was based on 1:200,000-scale geological maps, as well as a map showing the nature of the near-surface strata (Agster 1996). Areas with a shallower water table were defined for both model areas with the help of topographic maps with scales of 1:25,000 and 1:50,000 (areas designated as wetlands) and the geological maps mentioned above (areas designated as moors). The distribution of open-water surfaces and surface sealing by buildings or other forms of construction were also determined with the aid of topographic maps. Data on the distribution of precipitation were obtained from the German Weather Service (Deutscher Wetterdienst, DWD).

The total area investigated comprises the catchment areas of several major rivers and lakes (Fig. 2), and their discharge was recorded by a total of 21 water gauges.

The amount of groundwater recharge is significantly influenced by climatic trends. For a proper worst-case/best-case evaluation of the effects of groundwater withdrawal on the water budget of the area, the balance period must be integrated into long-term climatic trends. Climatic conditions, including those dominant during the balance period, are shown in Fig. 7, which compares precipitation at the Trittau station (southeastern Holstein) with regional precipitation in the Pinneberg and Luebeck areas, for water years 1954–1991. The straight lines represent the arithmetic means for this time period (Pinneberg area: 781 mm/a; southeastern Holstein: 759 mm/a; Luebeck area: 643 mm/a). The years 1970–1978 were rather dry, whereas precipitation was significantly above the long-term mean from 1979 to 1991. The regional precipitation value used for the Grosshansdorf model area (778 mm/a) is somewhat higher than the long-term mean from the station in Trittau. For the balance period chosen for modeling the entire region (shown as a closed bar in Fig. 7), mean annual precipitation in the region west of Hamburg amounted to approximately 810 mm, with rates of about 782 mm/a in southeastern Holstein, and about 688 mm in Luebeck. The distribution of groundwater recharge was therefore estimated for a relatively humid climatic period.

Distribution of Groundwater Recharge in the Total Area of Southeastern Holstein

The area studied comprises 1,392 km^2, with 87 grid cells each measuring 16 km^2. The location of the grid elements is shown in Figs. 5 and 8. Due to the size of the individual grid elements, the spatial resolution of the system properties in the model is low, i.e., specific local features were not able to be included. Nevertheless, regional differences are evident. In the entire study area, the percentage of sandy soils, where field utilization includes grassland, is 28.7%. Sandy forest soils comprise only a minor proportion. Their share of the total surface of the study area amounts to approximately 9%. Clayey soils represent 53% of the study area, with field/grassland utilization accounting for 44% and forest utilization another 9%. The highest percentage of forest areas in a grid element is 59% (Sachsenwald, located between the towns of Aumühle, Schwarzenbek, and Geesthacht).

Long-term precipitation rates were determined using the data recorded at a total of 24 weather monitoring

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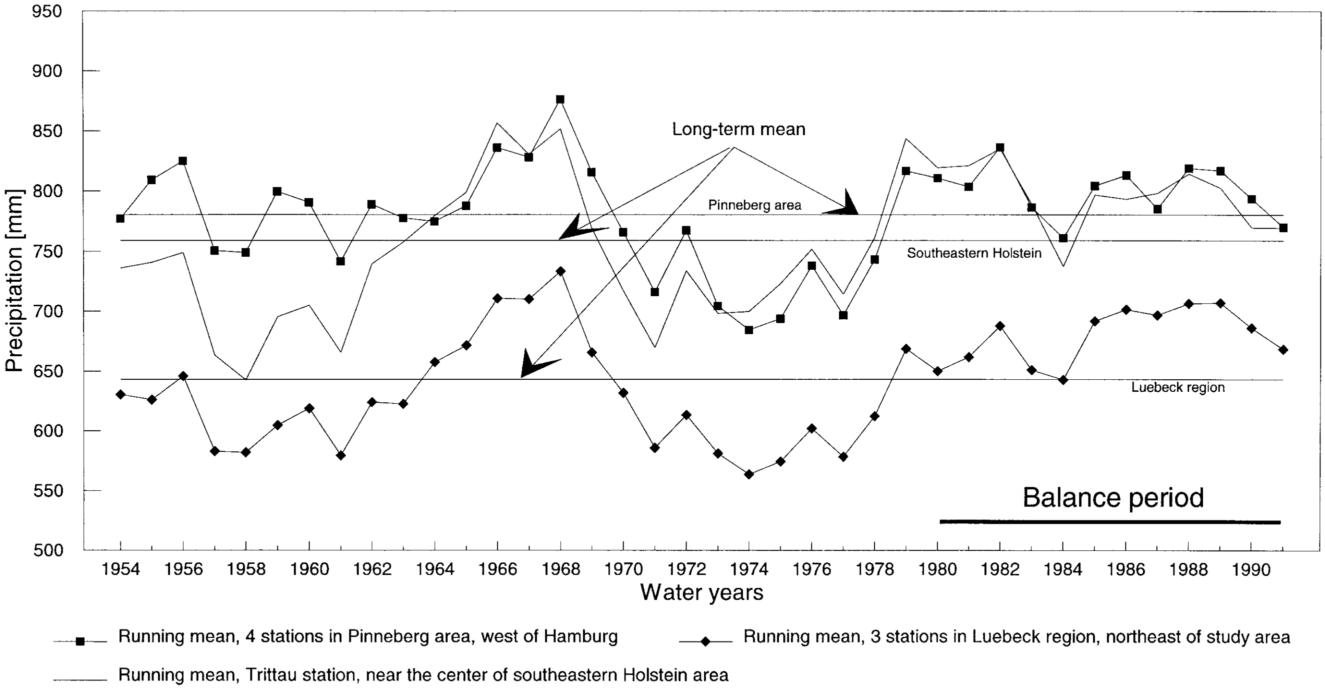

Fig. 7 Hydrographs of mean annual precipitation from 1954 to 1991 in the Pinneberg area (west of Hamburg), in the southeastern Holstein area (east of Hamburg), and in the Lübeck region to the northeast of the study area

points. The minimum value in this period was 687 mm/a, the maximum value 886 mm/a. In the northwestern part of the area investigated, the highest precipitation rates were recorded, more than 850 mm/a. From there to the east, southeast, and south precipitation amounts decrease almost continuously. In the Elbe River valley south of the southeastern Holstein moraine district (geest), precipitation rates are between 700 and 750 mm/a, with similar rates obtained to the northeast near the city of Lübeck. Mean annual precipitation in all grid cells in the area investigated amounted to 782 mm/a.

The potential rate of percolation water (as an integral of the study area) amounts to 333 mm/a in the balance period. The minimum and maximum values are 180 and 464 mm/a, respectively. The mean annual regional precipitation of 782 mm/a results in an average amount of evapotranspiration of 449 mm/a.

During the balance period from 1980 to 1991, the grid-cell-related discharge of surface runoff, including interflow, comprises 143 mm/a on average. The minimum value is 45 mm/a, the maximum value 272 mm/a. Low Ro discharge rates occur mainly south of the line extending from Aumühle to Schwarzenbek, located in the southern portion of the study area. In this undulating landscape of relatively old moraines, relief energy is relatively low. In addition, surface layers are primarily sandy, thus leading to the increased infiltration of precipitation. The highest discharge rates occur in the northern part of the study area, where cohesive sediments, including till and basin clay, dominate near the surface and the infiltration capacity of the soils is low. Moreover, the landscape in this area of young moraines from the last glacial period is characterized by relatively high relief energy which favors increased direct runoff. The lowlands northwest of the study area (Ammersbek River), and in both the southern Stecknitz River valley and south of the geest, all have high discharge rates of 200 mm/a and more.

The nonuniformity of surface-water discharge rates in the area investigated in southeastern Holstein is made evident by the relation between overland and underground runoff in the respective gauge catchments (Table 3). At a mean value of 1.6:1, the lowest value equals 0.1, i.e., overland runoff only accounts for approximately 8% of total runoff. The area in question is a partial catchment area of the River Bille located between the water gauges in Reinbek (No. 35) and Sachsenwaldau (No. 36). As a result of the orographically low position at the edge of the geest, strong groundwater exfiltration occurs from Pleistocene and Tertiary aquifers into the receiving channels against the background of artesian groundwater conditions. The same can be said of prevailing conditions in the partial catchment areas of the River Ammersbek (Aue) at the Bruegkamp gauge (No. 47; Alster lowlands) and near the Linau gauge in Witzeeze (No. 41; Stecknitz Valley). Here, the R_o/R_u ratio equals 0.4. The extent of underground catchment areas is uncertain. For this reason, discharge rates have been calculated on the basis of the size of catchment areas above ground. Apparently, high groundwater discharge rates from small catchment areas may also be due to the fact that underground catchment areas are more extensive than the overland areas which have been taken as the basis for the calculation.

The Bunsbach River at the Rehagen gauge (No. 37) southwest of Bargteheide and the Grienau River at the

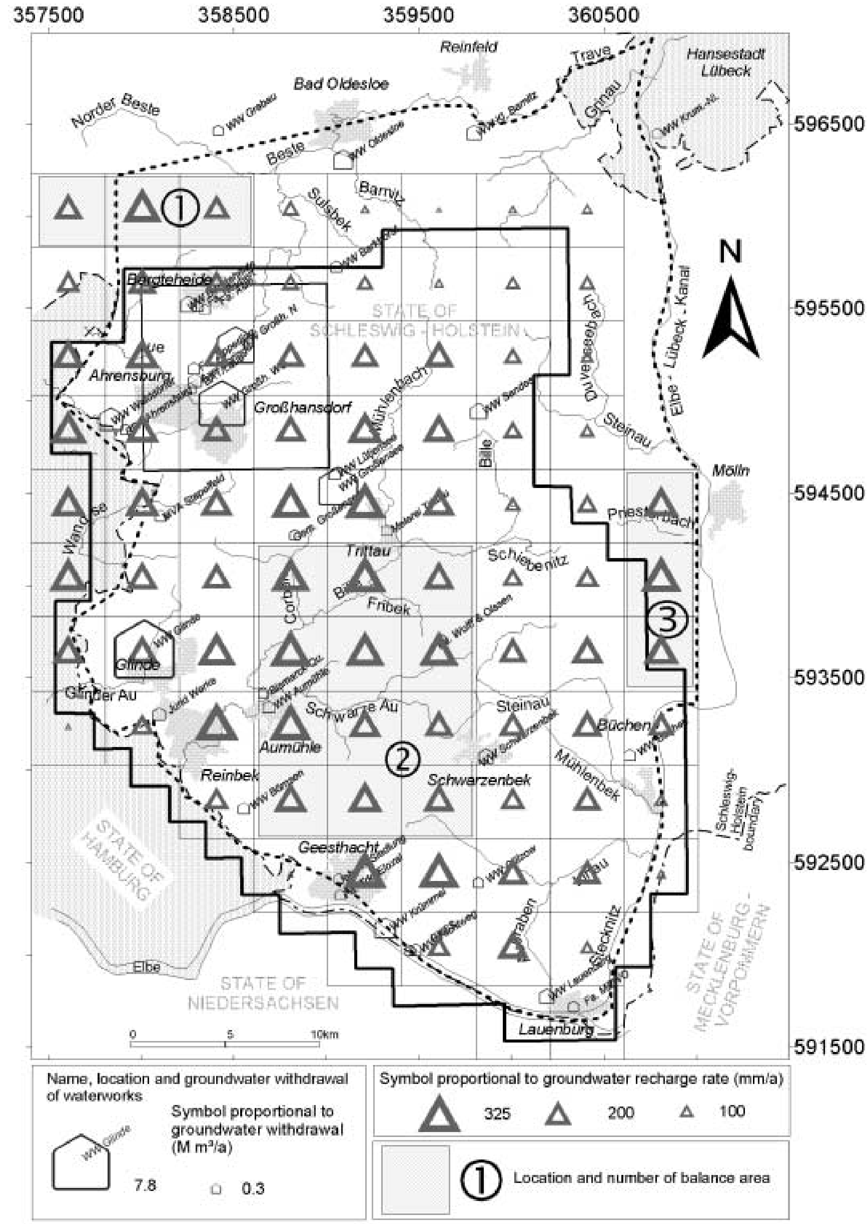

Fig. 8 Comparison of groundwater withdrawal and groundwater recharge rates in the study area

Ziegelhof gauge (No. 38) in the northeastern portion of the area studied show respective R_o/R_u ratios of 3.7 and 3.0, i.e., overland runoff is three to four times higher than underground runoff. Whereas influent conditions characterize parts of the Bunsbach catchment area, a cohesive surficial layer of low permeability occurs in the Grienau catchment area. Both conditions result in a reduction of groundwater discharge.

The above-mentioned considerations demonstrate that the comprehensive collection of runoff-activity data is of particular importance in investigations concerning water budgets. In contrast, runoff estimates based on data given in the literature may lead to a wide range of results, thus limiting their utilization in the field of hydrological planning. The heterogeneous nature of discharge rates in the southeastern Holstein area which was investigated (Table 3) also illustrates that runoff data can not simply be transferred to neighboring catchment areas. This mean that a comprehensive network of water gauges is required for the entire area.

For purposes of calculating groundwater recharge, runoff data collected for the surface-water catchment areas were transferred to the model grid (Fig. 5). The difference between potential amounts of percolation water and surface runoff was used to represent the groundwater recharge rate for each grid cell. The northeastern as well as the southern and southeastern portions of the study area are characterized by low groundwater recharge rates (Fig. 8). On the southern edge, south of the geest (River Elbe and River Stecknitz lowlands), this is due to the fact that the share of surfaces underlain by shallow water tables is particularly large, resulting in above-average

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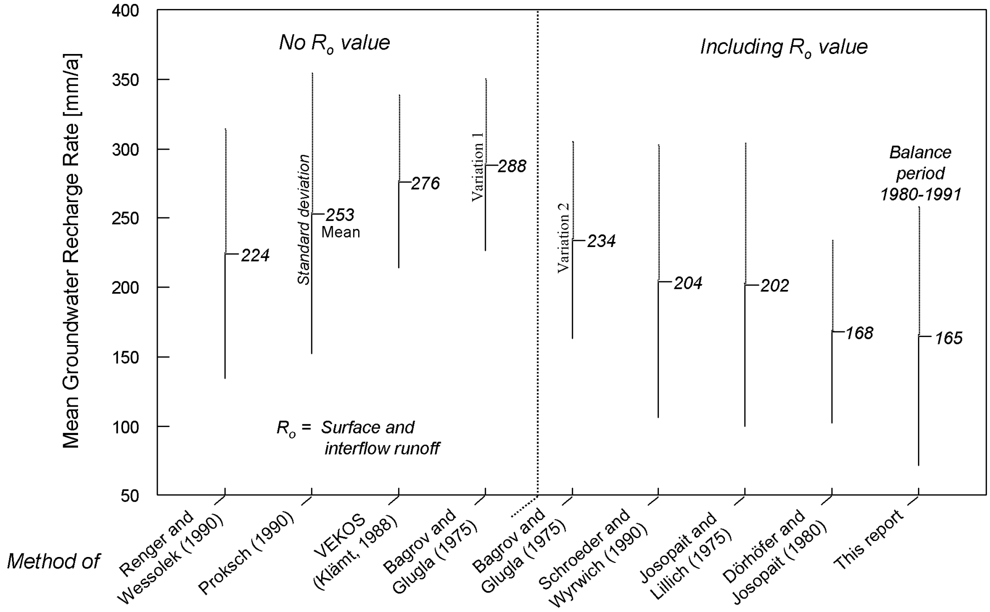

Fig. 9 Comparison of average groundwater recharge rates for the area studied in southeastern Holstein in this report from 1980 to 1991, with results from other methods calculated according to Meyer and Tesmer (2000) from 1961 to 1990

evaporation. In addition, regional precipitation in this area equals 708–751 mm/a, well below the mean value of 782 mm/a determined for the entire area. To the north and northeast the extensive occurrence of cohesive surface layers and resulting higher evaporation rates lead to a decrease in the potential amount of percolation water. At the same time, overground runoff is also higher than in the remainder of the study area. Both factors result in low groundwater recharge rates. On the western and eastern edges, between Geesthacht and Schwarzenbek, and in the central region of the study area, north of the line extending from Aumühle to Schwarzenbek, groundwater recharge rates amount to 250 mm/a, well above the mean value of 165 mm/a calculated for this area. In the central part as well as to the east, and on the southern edges of the area, this correlates well with the extensive distribution of sandy soils.

Comparison of Results with Other Methods

In the southeastern Holstein hydrogeological planning area (Fig. 2), groundwater recharge was calculated under the auspices of the State Agency for Nature and Environment (LANU) for the period 1961–1990 and on the basis of several methods (Meyer and Tesmer 2000). The method introduced by Renger and Wessolek (1990) is based on long-term analyses of the relationship between soil moisture and soil-moisture tension, from which they formulated equations to calculate actual evapotranspiration. The VEKOS evapotranspiration model used at the German Meteorological Office (DWD) reduces crop-specific potential evapotranspiration in relation to available water content (Klämt 1988). For the estimation of actual evapotranspiration rates according to variation 1 of the model developed by Bagrov and Glugla (1975), values are required for potential evapotranspiration, precipitation, and soil texture. Actual evapotranspiration rates can then be calculated using nomograms. For each of these three methods groundwater recharge is then calculated as the difference between precipitation and actual evapotranspiration. Proksch (1990) uses lysimeter equations to calculate amounts of percolation water. All of these methods assume that there is no surface runoff.

The methods of Josopait and Lillich (1975), Dörhöfer and Josopait (1980), and Schroeder and Wyrwich (1990) use either lysimeter equations or estimated values for actual evapotranspiration rates dependent on vegetation and soil texture. In contrast to the first-mentioned methods, these latter methods include surface runoff in their estimations. Variation 2 of the method developed by Bagrov and Glugla (1975) also takes surface runoff into account by including runoff data. The other methods estimate direct runoff by means of surface slope or surface relief, soil texture, and vegetation, and Schroeder and Wyrwich (1990) also incorporate land-utilization data.

The results of these calculations are summarized in Fig. 9 by showing mean and standard deviations. In addition, the results of new calculations presented in this paper are shown (Fig. 9; right-hand column). The mean values of the methods which exclude direct runoff range from 224 to 288 mm/a. The highest standard deviation is obtained by the method of Proksch (1990). Methods which include direct runoff inevitably give lower results. Here, the highest mean value of the groundwater recharge rate is 234 mm/a (Bagrov and Glugla 1975), and the lowest 168 mm/a (Dörhöfer and Josopait 1980). Even though recharge rates in this study were calculated for a period with above-average precipitation rates (Fig. 7), the results obtained (165 mm/a) are low in comparison with other time periods.

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Groundwater Recharge in the Grosshansdorf Model Area

For the Grosshansdorf model area (Fig. 2; square border) regional precipitation rates were determined using the data recorded by a total of 12 weather monitoring stations. The regional distribution of the long-term means was calculated in node form by means of geostatistical methods. Each cell comprises one precipitation data point. The integral mean determined for the study area resulted in precipitation rates of 778 mm/a with a standard deviation of ±0.7%. The minimum value of all grid cells was 760 mm/a, the maximum value 792 mm/a. Precipitation rates and system characteristics, as derived from geological and topographic maps which were described above, thus made it possible to calculate potential percolation-water amounts in accordance with Table 4.

In the Grosshansdorf model area the mean potential amount of percolation water is 330 mm/a (Table 2; lysimeter equations of Dyck and Chardabellas 1963), with a range of 230 to 477 mm/a. In the valley plain area (Hunnau/Aue) with shallow water tables as well as in wetlands, potential percolation water amounts to approximately 200 to 300 mm/a. Locations with deep water tables and a sandy surface layer, however, show large amounts of percolation water of as much as 400 mm/a.

Potential percolation rates from the Grosshansdorf model area were also calculated on the basis of lysimeter equations developed by other authors which were mentioned above. Corresponding results are shown in Table 2 (left-hand column). Using the lysimeter equations of Dyck and Chardabellas (1963) leads to higher total amounts of percolation water than using the above equations. For the regional mean this difference is approximately 34 mm/a or 10%. Minimum and maximum values differ by 25 mm/a each. Hence, in hydrological planning, water managers must also consider the fact that using the approach of Josopait and Lillich (1975) may result in higher groundwater-availability values.

Discharge rates were also recorded in the Grosshansdorf model area on the basis of gauge measurements. Distinctions were made between surface and underground discharge according to Kille (1975). Calculated on this basis, mean discharge rates (R_o) in the model area are 161 mm/a, minimum rates are 92 mm/a, and maximum rates are 265 mm/a.

In order to calculate groundwater recharge rates, the difference between potential percolation water levels and surface runoff was determined for each grid cell. Large groundwater recharge rates are obtained for grid elements with primarily sandy surface layers and field/grassland utilization, because evaporation and surface runoff are low in these areas. However, in areas with high surface runoff and shallow water tables, e.g., in valleys and lowlands, groundwater recharge rates are low, even to the extent of producing negative water balances, i.e., evaporation and surface runoff exceed precipitation amounts. The mean groundwater recharge rate in the Grosshansdorf model area amounts to 168 mm/a. This equals 18.5 million m^3/a or 21.6% of mean annual precipitation (P). The maximum value is 374 mm/a or 48% of P.

Groundwater Balance and Conclusions for Groundwater Exploitation

Water balances were calculated for the three subareas with relatively high groundwater recharge rates shown in Fig. 8 (hatched areas) on the basis of groundwater recharge calculations. At present these areas are not used for the exploitation of drinking water because they are not located in the vicinity of an urban supply area (e.g., outskirts of Hamburg). Based on the estimated values for groundwater recharge and runoff (R_u), estimates of the differences among these subareas must be assessed with respect to the potential for drinking-water exploitation. From the ecological point of view, groundwater discharge into surface waters represents an important element of the water balance. A decrease in average low-water runoff due to groundwater withdrawal may result in serious damage to flora and fauna in a catchment. The depth, hydraulic properties, and distribution of usable aquifers have not been considered in the estimate presented here.

Area 1 is 48 km^2 in size and is located north of Bargteheide on the northern edge of the area investigated. In this area, the estimated groundwater recharge rate is approximately 10.9 million m^3/a, and subsurface flow to surface waters amounts to 10.1 million m^3/a. If substantial amounts of groundwater were withdrawn in this area, the consequence would be a reduction in average low-water runoff.

Area 2, measuring 208 km^2, is located in the central part of the study area and comprises the areas between Aumühle, Schwarzenbek, and Trittau. The main receiving channels are the Schwarze Au River and the Bille River. The hypothetical groundwater recharge rate equals 49.7 million m^3/a, and subsurface flow into the receiving channels amounts to 21.5 million m^3/a. The remaining 28 million m^3/a runs off as subsurface flow via the edges of the area, or into deeper aquifers. If a major groundwater withdrawal plant were constructed in this area, only indirect effects on the hydrological cycle close to the surface would be anticipated. This applies particularly to the southern part of this area. Subsurface flow from the geest into the Elbe Valley would be reduced by this withdrawal of groundwater, however, and the resulting decrease in groundwater levels close to the surface would be so negligible (only a few centimeters) that it would have no detrimental effects on the ecological system (cf. DVWK 1987).

Area 3, located on the eastern edge of the study area and west of the Elbe-Luebeck Canal, unlike area 1, shows more favorable possibilities for water exploitation with respect to the shallow groundwater balance. In this area, which also measures 48 km^2, the hypothetical groundwater recharge rate amounts to 12.8 million m^3/a,

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and subsurface flow into tributaries equals 3.8 million m^3/a. This means that approximately 9 million m^3/a flows off as subsurface flow via the edges of the area, exfiltrates into the Elbe-Luebeck Canal, or moves into deeper aquifers, if the necessary head-potential difference exists. If hydrogeological conditions are favorable, it is also possible to exploit groundwater here without incurring detrimental ecological effects.

The average groundwater recharge rate in the Grosshansdorf model area is 18.5 million m^3/a. Of these water quantities, approximately 12 million m^3, 65% of the water available, is drawn into the public water-supply system. Any increase in groundwater withdrawal in this region would lead to further reductions in groundwater levels. In addition, even lower low-water flow rates are anticipated for the future. For these reasons, the available groundwater supply in this region is currently exploited to the fullest reasonable extent.

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