Hydrology in the Lower Jordan River Basin: About actual water resources and new water sources - an analysis based on the TRAIN-ZIN model

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Abstract Different water balance components of the lower Jordan River basin (LJRB) were estimated and maped for the wet extreme season 1991/92, the drought season 1998/99 and the average rainfall season 2002/03. Based on regionalized and calibrated precorrected rainfall radar data a map on rainfall (mm/a) was produced. Through the application of the TRAIN-ZIN model, maps with the following parameters were produced for all the three seasons as well with the mean values of the three seasons: evapotranspiration (mm/a), percolation (mm/a), overland flow (mm/a), wadi runoff (mm/a). TRAIN-ZIN simulations were also used to estimate the potentials for rural rainwater harvesting (R-RWH) during the drought season 1998/99 and average rainfall season 2002/03. Based on rainfall radar data maximum potentials for urban rainwater harvesting (U-RWH) as well as areas suitable for rainfed agriculture were caluclated. Apart, the potential for managed aquifer recharge via surface infiltration was simulated.

Keywords Rainfall radar, evapotranspiration, overland flow, percolation, wadi runoff, Lower Jordan River Basin, TRAIN-ZIN model, surface water balance, urban rainwater harvesting, rainfed agriculture, managed aquifer recharge, surface infiltration, rural rainwater harvesting, hillslope conduit system, microcatchment system.

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1 Introduction

No detailed, basin-wide overview of naturally available surface water resources currently exists for the Lower Jordan River Basin (LJRB). In the frame of the GLOWA Jordan River Project water balance components (rainfall, evapotraspiration, percolation, overland flow and wadi runoff) of the LJRB were estimated and maped for the following rainfall seasons:

- high rainfall season 1991/1992 (wet extreme season),
- low rainfall season 1998/1999 (drought season),
- average rainfall season 2002/2003;

- an averaging dataset of the three seasons is included

Based on the rainfall data, areas suitable for rainfed agriculture were maped. Based on the water balance components, the maximum potentials for the following new water sources could be estimated:

- rural rainwater harvesting (R-RWH) with hillslope conduit system and microcatchment systems,
- urban rainwater harvesting (U-RWH),
- managed aquifer recharge (MAR) via surface infiltration.

Some results were already presented in a poster during the the Final Conference of the GLOWA Jordan River Project in Limassol, Cyprus, 5-7 September 2011, the one is annexed to this paper.

2 Methodology

Here a short summary of the methodology is given. The methodology used to calculate the water balance component values (rainfall, evapotranspiration, percolation, overland flow, and wadi runoff) are described in more detail at Gunkel & Lange (2012). U-RWH was calculated according to Lange et al. (2012).

2.1 Water balance component - Rainfall

A C-Band volume scanning rainfall radar system located at Ben-Gurion international airport, close to Tel Aviv, was used as a data source. The resolution is 1.4°x 1 km in space (polar coordinates), including different elevation angles, and 5 min scan time. Radar data was obtained from E. Morin (Hebrew University of Jerusalem, Israel) after pre-correction by a multiple regression approach (Morin & Gabella 2007). Pre-corrected data was then regionalized to the LJRB and calibrated by station data at 39 to 90 locations, depending on the season. Differences in calibration factors were smoothed by conditional merging (Goudenhoofdt & Delobbe 2009). Only areas inside an effective range (150 km) of the rainfall radar were considered. Three climate seasons were analysed: The hydrological year 2002/03 served as an average season, 1991/92 as a wet extreme and 1998/99 as a drought season. Also an averaging dataset of the three seasons is included.

2.1.1 Areas suitable for rainfed agriculture

Areas where seasonal rainfall exceeded 400 mm were assumed to be suitable for rainfed agriculture. These were outlined for the 1998/99 drought and the 2002/03 average season.

2.2 Water balance component - Evapotranspiration

Evapotranspiration was simulated by a modified TRAIN model. The original TRAIN (Menzel et al. 2009) was modified including the Shuttleworth-Wallace equation (Shuttleworth & Wallace 1985). First, the amount of water stored in the canopy was assessed, from which evaporation losses according to Penman equation were calculated. Thereby a seasonal development of the Leaf Area Index (LAI) determined the interception capacity for different vegetation types. Second, the Shuttleworth-Wallace equation calculated evapotranspiration from sparsely vegetated areas (soil evaporation and plant transpiration). Available soil moisture was obtained from the soil moisture module. Three climate seasons were simulated: The hydrological year 2002/03 served as an average season, 1991/92 as a wet extreme and 1998/99 as a drought season. Also an averaging dataset of the three seasons is included.

2.3 Water balance component - Percolation

Percolation was simulated by the TRAIN-ZIN model. Modelling was performed in grid cells of 250 x 250 m². Here, percolation is defined as water volume that percolates from the upper root zone which is influenced by evapotranspiration. In the TRAIN-ZIN this is conceptualized by the central soil module. Evapotranspiration was modeled by TRAIN using a daily timestep, whereas losses by overland flow generation and percolation, were related to ZIN and had a higher temporal resolution, at the time interval of the rainfall input, 5 to 7 min. For every grid cell, percolation volumes were aggregated to seasonal values. They should be seen as maximum estimates for groundwater recharge, since on the way to the aquifer additional losses may occur. Three climate seasons were simulated: The hydrological year 2002/03 served as an average season, 1991/92 as a wet extreme and 1998/99 as a drought season. Also an averaging dataset of the three seasons is included.

2.4 Water balance component - Overland flow

Overland flow was simulated by the TRAIN-ZIN model and performed in grid cells of 250 x 250 m² at the time interval of the rainfall radar input, 5 to 7 min. This high resolution was required to adequately represent the dominating hydrological processes, namely Hortonian and saturation excess overland flow generation. After initial loss by surface detentions was filled, infiltration excess overland flow was calculated comparing rainfall intensity with infiltration rate. When the soil storage was filled, saturation excess overland flow was simulated. Model parameters were determined by specifying constant infiltration rates and values for maximum initial losses for all grid cells based on land use and soil information. Values common in the literature were used to define infiltration potentials of soil types. If land use type dominated overland flow generation (e.g. for urban areas), infiltration values were chosen independent of soil type. In other cases, soil-dependent infiltration rates were modified according to a land use factor, e.g. increased for agricultural areas. For every grid cell, generated overland flow was aggregated to seasonal values. Three climate seasons were simulated: The hydrological year 2002/03 served as an average season, 1991/92 as a wet extreme and 1998/99 as a drought season. Also an averaging dataset of the three seasons is included.

2.5 Water balance component - Wadi runoff

Wadi runoff was simulated by the TRAIN-ZIN model. For this purpose, overland flow calculated for all grid cells was concentrated in sub-basins and transferred to corresponding channel segments. Runoff concentration was performed by a synthetic unit hydrograph considering slope and area of the sub-basins. Within the channels, routing was achieved by the non-linear, implicit Muskingum-Cunge method (Ponce & Chaganti 1994). Transmission losses were quantified and subtracted as instantaneous infiltration using the Green-Ampt approach (Green & Ampt 1911). For predefined channel nodes, runoff volumes were aggregated to seasonal values and displayed along the wadis. Three climate seasons were simulated: The hydrological year 2002/03 served as an average season, 1991/92 as a wet extreme and 1998/99 as a drought season. Also an averaging dataset of the three seasons is included.

2.6 New water source – Urban rainwater harvsting

For the entire LJRB, a contiguous Geographical Information System (GIS) data layer of urban areas combining different data sources was created. For the Israeli part, a vector data set of 2002 delineated buildings as a distinct class. Urban areas of the Palestinian Authority (PA) were digitized from aerial photos with a spatial resolution of 1×1m². In Jordan, urban areas were extracted as a distinct pixel value class (78×78 m²) from a 2002 land use map and converted to vector data. A C-Band volume scanning rainfall radar system located at Ben-Gurion international airport, close to Tel Aviv, provided regional data sets of 1.4° × 1 km (polar coordinates) rainfall during an average season (2002/2003) and during a drought (1998/1999). The Jordanian parts of the LJRB outside a 150 km range around the location of the rainfall radar had to be excluded due to uncertainties in rainfall estimates. For both rainfall seasons, a GIS overlay of 1×1 km² annual rainfall volumes and the urban vector data set yielded the annual rainfall that fell on urban areas. This data set was multiplied by factor 0.2 due to the fact that approximately 20% of urban areas in the Middle East are covered by roof areas (Grodek et al. 2011). To obtain volumes of U-RWH, the data was multiplied by a variable roof runoff coefficient RC. RC was varied according to a linear regression found between annual rainfall amount and simulated RC of the rainfall stations in Ramallah. Thereby, the lower boundary for the RC values was set at 0.7 and the upper boundary at 0.9.

2.7 New water source – Rural rainwater harvesting

R-RWH potential are calculated as generated hillslope runoff from the TRAIN-ZIN model. Runoff depends on soil properties, landuse and topography. Urban areas are excluded. Rainfall radar (5 min) data serves as input. Downstream effects are not included. Applicable techniques depend on slope. Examples for two techniques are as follows:

- for slopes < 5 %: Microcatchment systems,
- for slopes > 10 %: Hillside conduit systems.

2.8 New water source – Managed aquifer recharge

The input parameters surface lithology, topography, urban areas and availability of water resources were processed to thematic layers, which were then combined using a GIS-based overlay approach. The resulting map delineated areas of distinct MAR suitability classes. Hydraulic properties of the surface lithology were derived from geological maps or were estimated based on information derived from literature. Hydrogeological units were classified into: aquifer, aquitard and aquifer/aquitard (locally varying). The latter class was referring to geological units with widely differing hydraulic characteristics due to post sedimentary processes (e.g. karstification). A high potential for MAR via surface infiltration was given to areas where an aquifer was combined with a slope < 5 %, a medium potential for the combination aquifer/aquitard (locally varying) and slope < 5 %. All areas classified as aquitard and/or a slope > 5 % were attributed with a low MAR potential. Urban areas and smaller settlements were considered as a restricting factor since it was assumed that surface infiltration required an appropriate amount of area. Therefore, urban areas were given a low MAR potential in the map.

Water from dams and wastewater treatment plants were regarded as water sources which can principally be utilized for MAR. Therefore, a 5 km buffer around the location of both existing and planned dams and wastewater treatment plants was used whereby only sites at a lower altitude than the respective water source were considered suitable. If those areas coincided with areas previously classified high (aquifer + slope < 5 %) the overlay assigned a very high potential for MAR. Wadi runoff as direct response to rainfall was simulated by TRAIN-ZIN and included along the channel network. This may serve as additional water source.

The needed data about geology was supplied by the Hebrew University of Jerusalem, the one about the location of planned reservoirs and wastewater treatment plants by the SMART project (Rapp 2008), the slope data comes from http://srtm.csi.cgiar.org.

3 Results

3.1 Water balance component - Rainfall

The rainfall radar maps derived for the hydrological year 1991/92 (wet extreme), 1998/99 (drought) and 2002/03 (average rainfall season) are described at Gunkel & Lange (2012). The mean of all three seasons are showed in Figure 1.

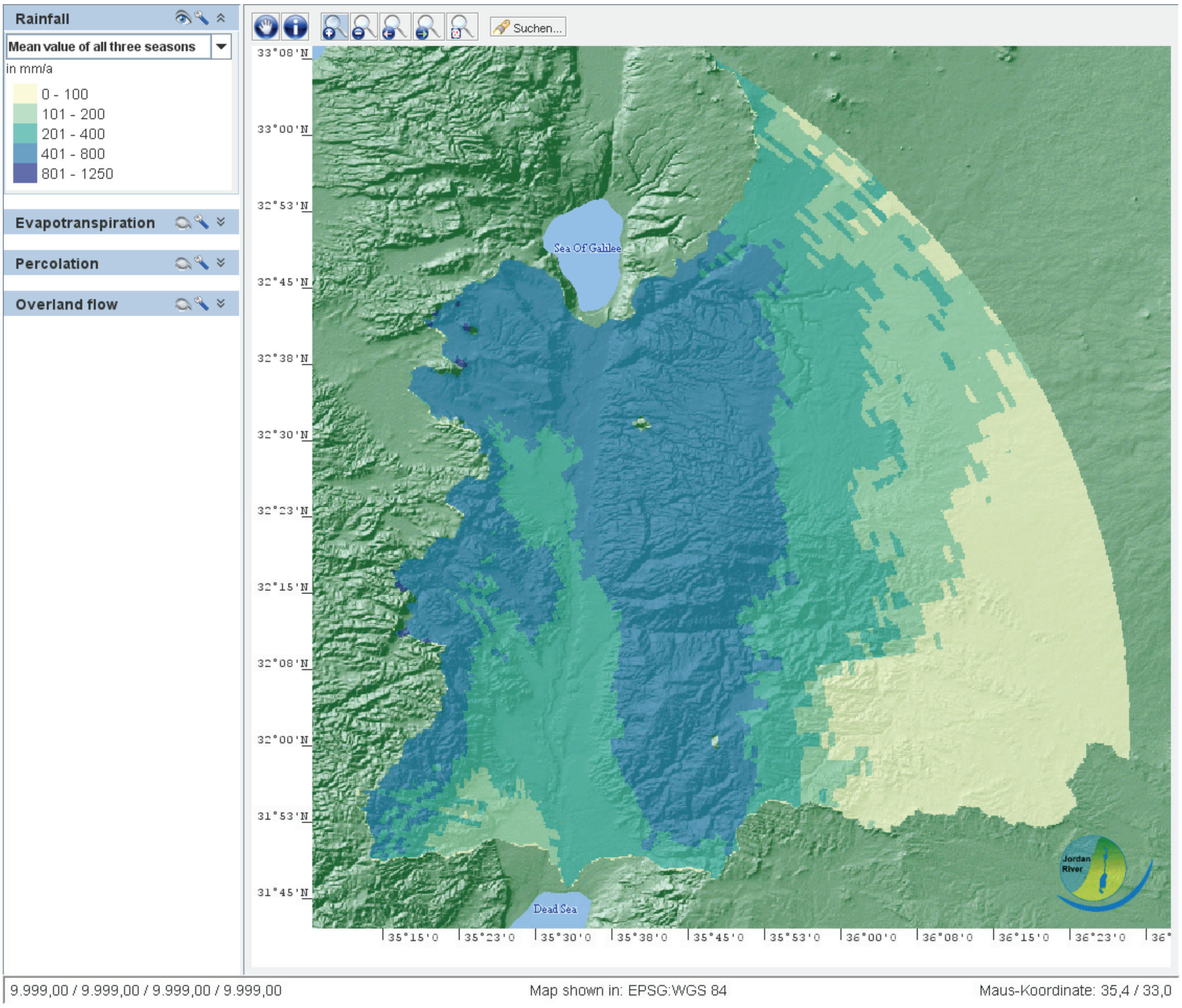

Figure 1 Averaging dataset of the rainfall radar maps (mm/a) for the hydrologial seasons 1991/92, 1998/99, 2002/03. The circular border of the values on the right indicates the effective range of the rainfall radar.

3.1.1 Areas suitable for rainfed agriculture

The suitability for rainfed agriculture during the hydrological season 1998/99 (drought) and 2002/03 (average rainfall season) are shown in Figure 2. Areas where seasonal rainfall exceeded 400 mm were assumed to be suitable for rainfed agriculture.

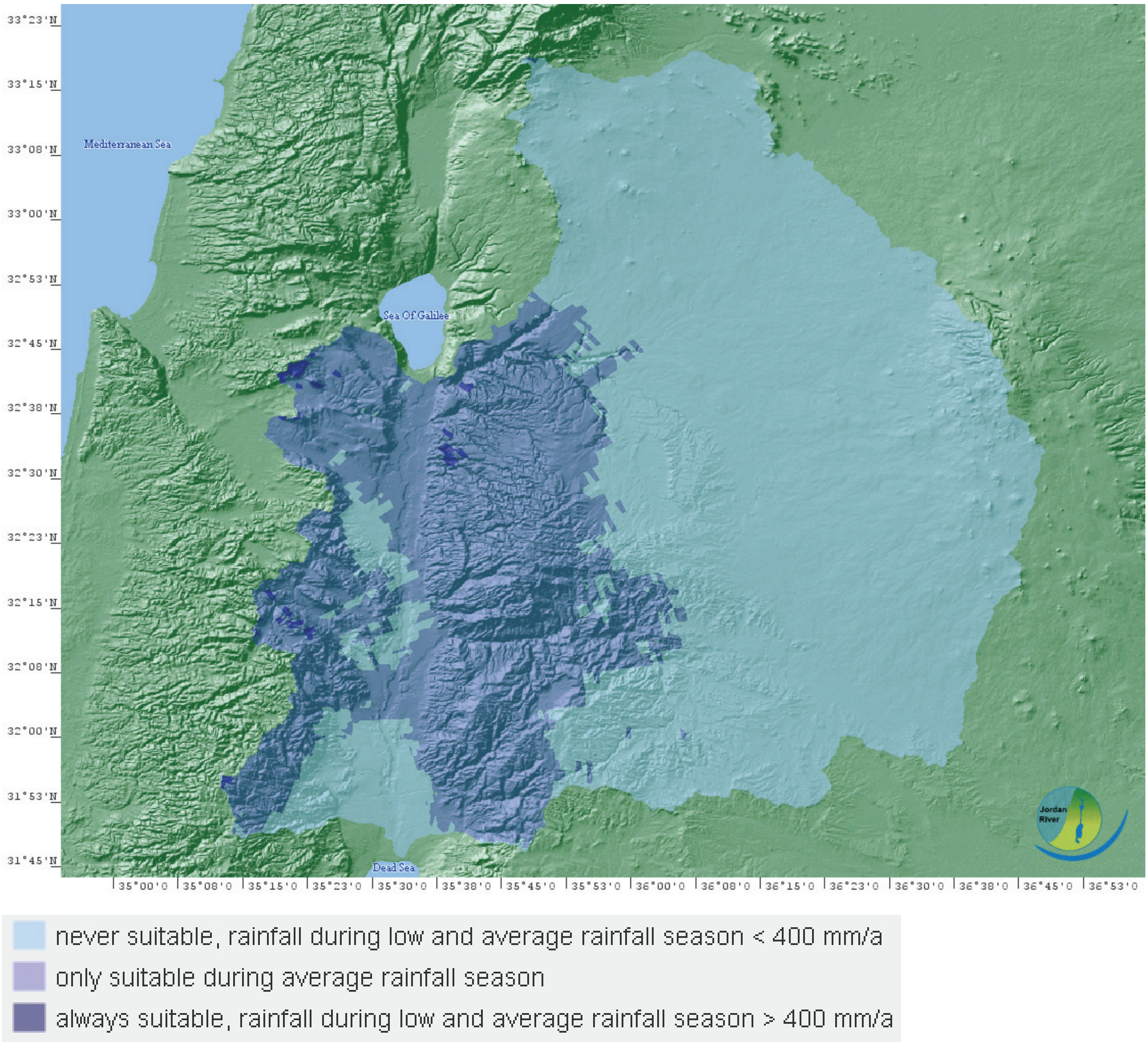

Figure 2 Suitability for rainfed agriculture during the low(1998/99) and average (2002/03) rainfall season.

3.2 Water balance component - Evapotranspiration

The amounts of evapotranspiration for the hydrological season 1991/92 can be seen in Figure 3, the amounts for the season 1998/99 in Figure 4, the amounts for the season 2002/03 in Gunkel & Lange (2012), and the mean amounts for all three seasons in Figure 5.

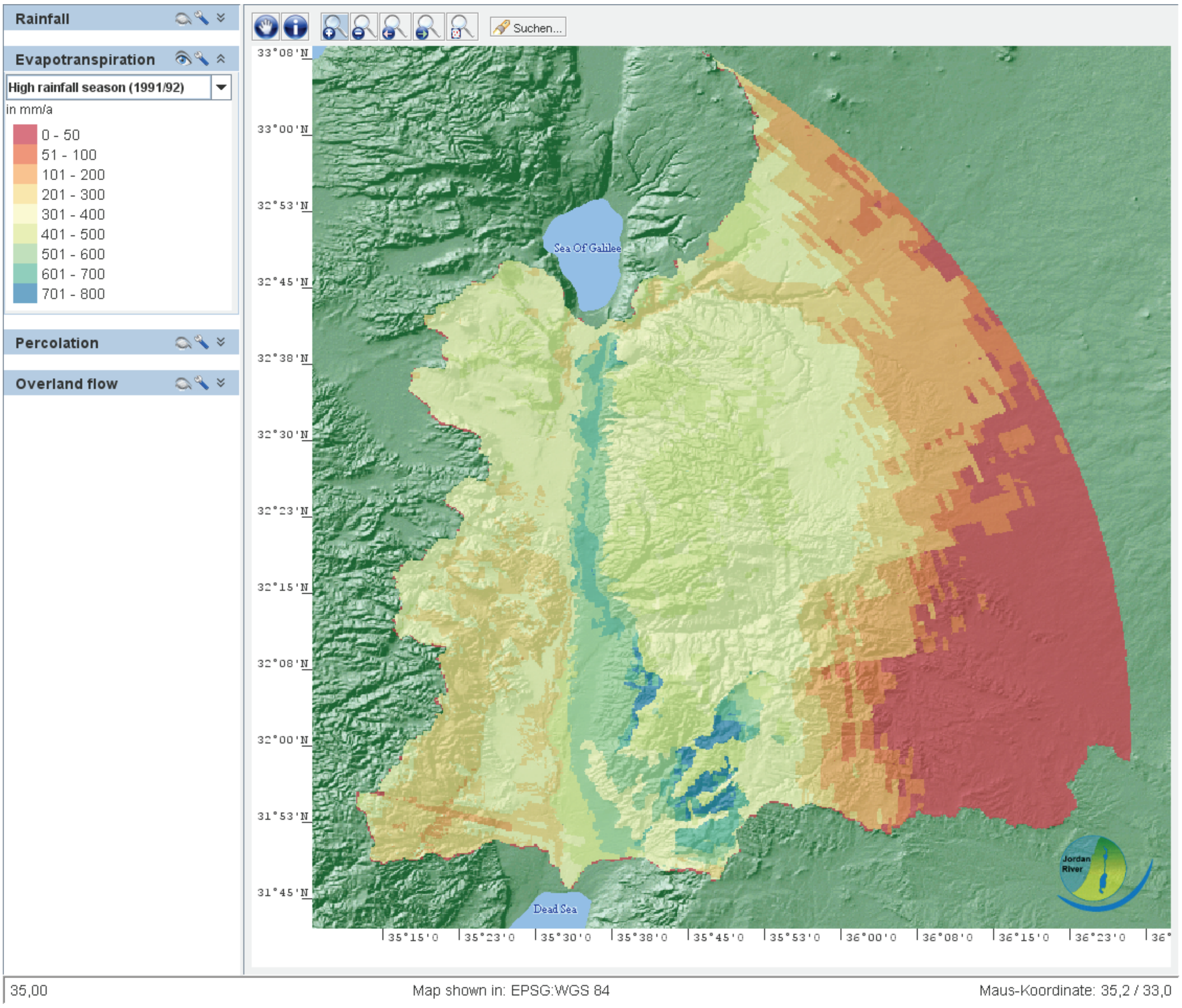

Figure 3 Amounts of evapotranspiration (mm/a) for the season 1991/92 (wet extreme). The circular border of the values on the right indicates the effective range of the rainfall radar.

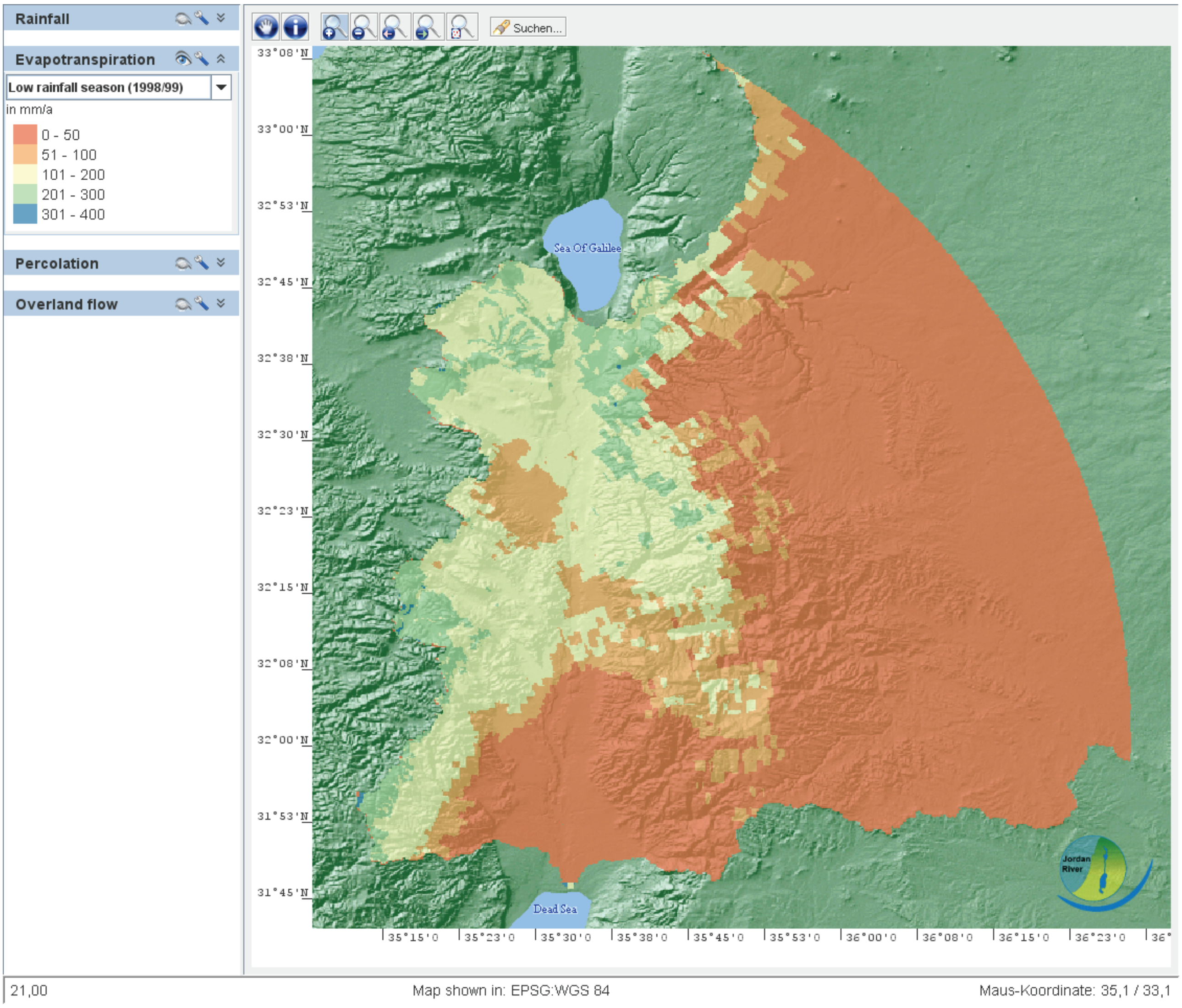

Figure 4 Amounts of evapotranspiration (mm/a) for the season 1998/99 (drought). The circular border of the values on the right indicates the effective range of the rainfall radar.

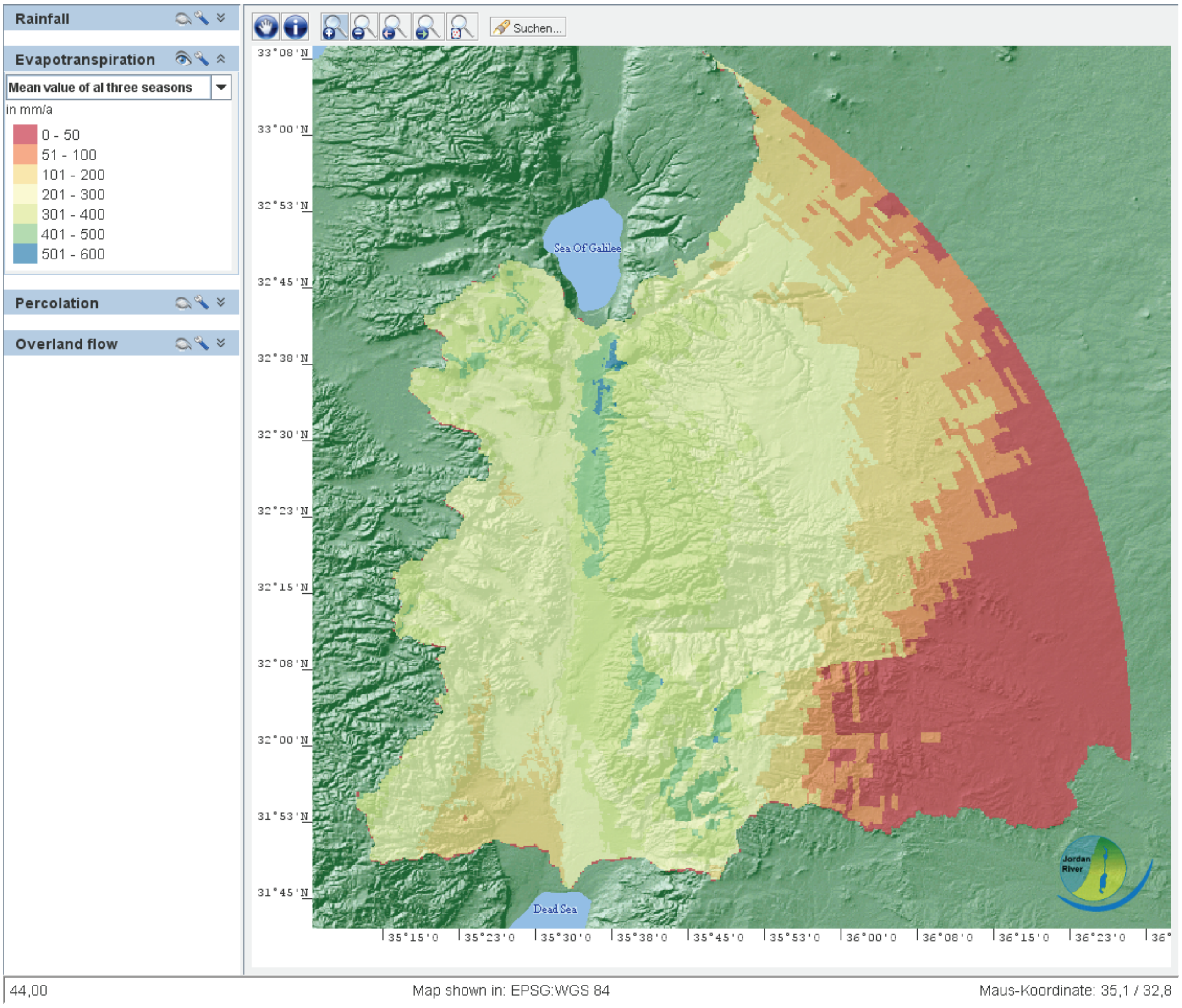

Figure 5 Average amounts of evapotranspiration (mm/a) for the three season 1991/92, 1998/99, 2002/03. The circular border of the values on the right indicates the effective range of the rainfall radar.

3.3 Water balance component - Percolation

The amounts of percolation for the season 1991/92 can be seen in Figure 6, the amounts for the season 1998/99 in Figure 7, the amounts of the season 2002/03 in Gunkel & Lange (2012), and the mean amounts for all three seasons in Figure 8.

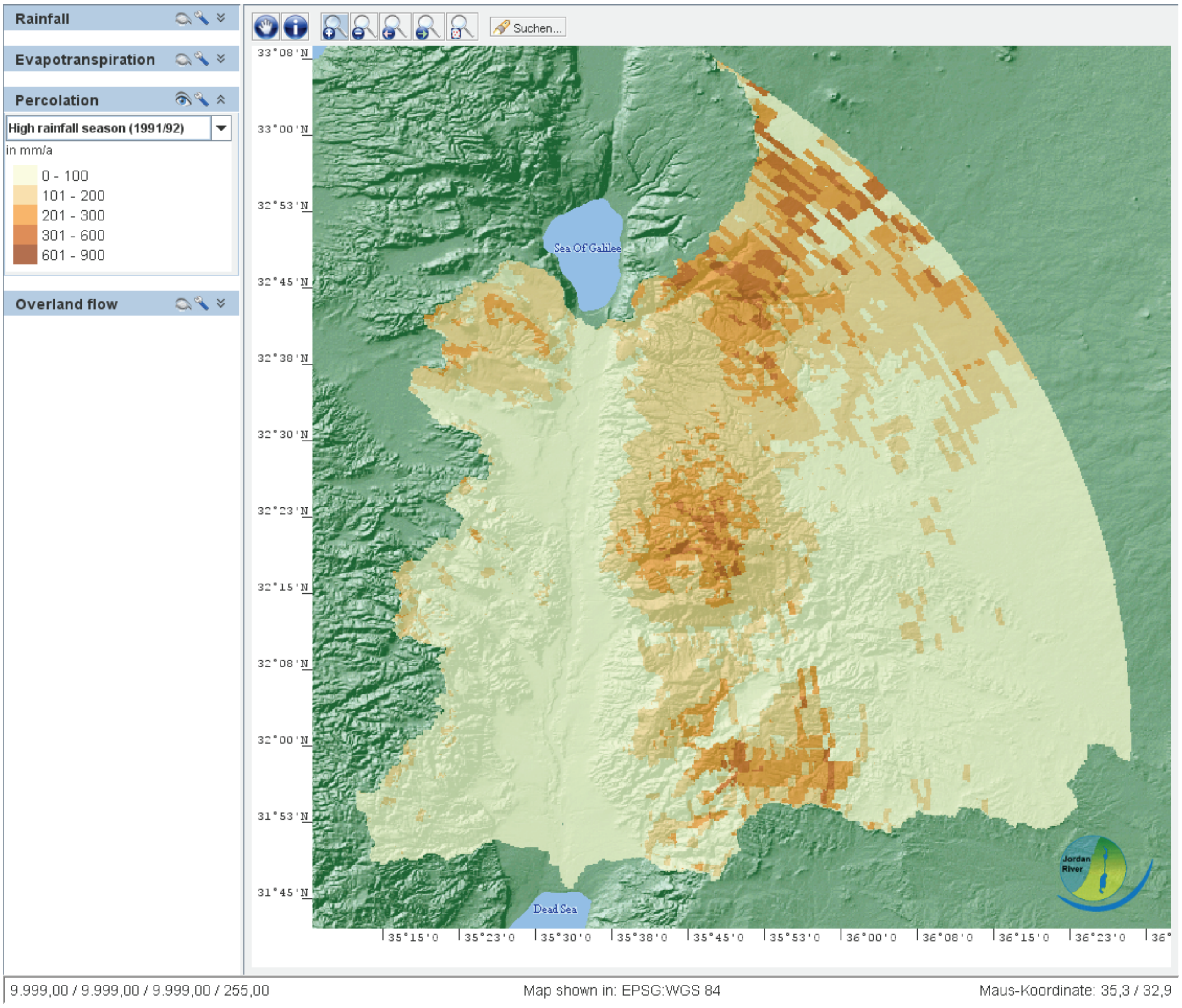

Figure 6 Amounts of percolation (mm/a) for the season 1991/92 (wet extreme). The circular border of the values on the right indicates the effective range of the rainfall radar.

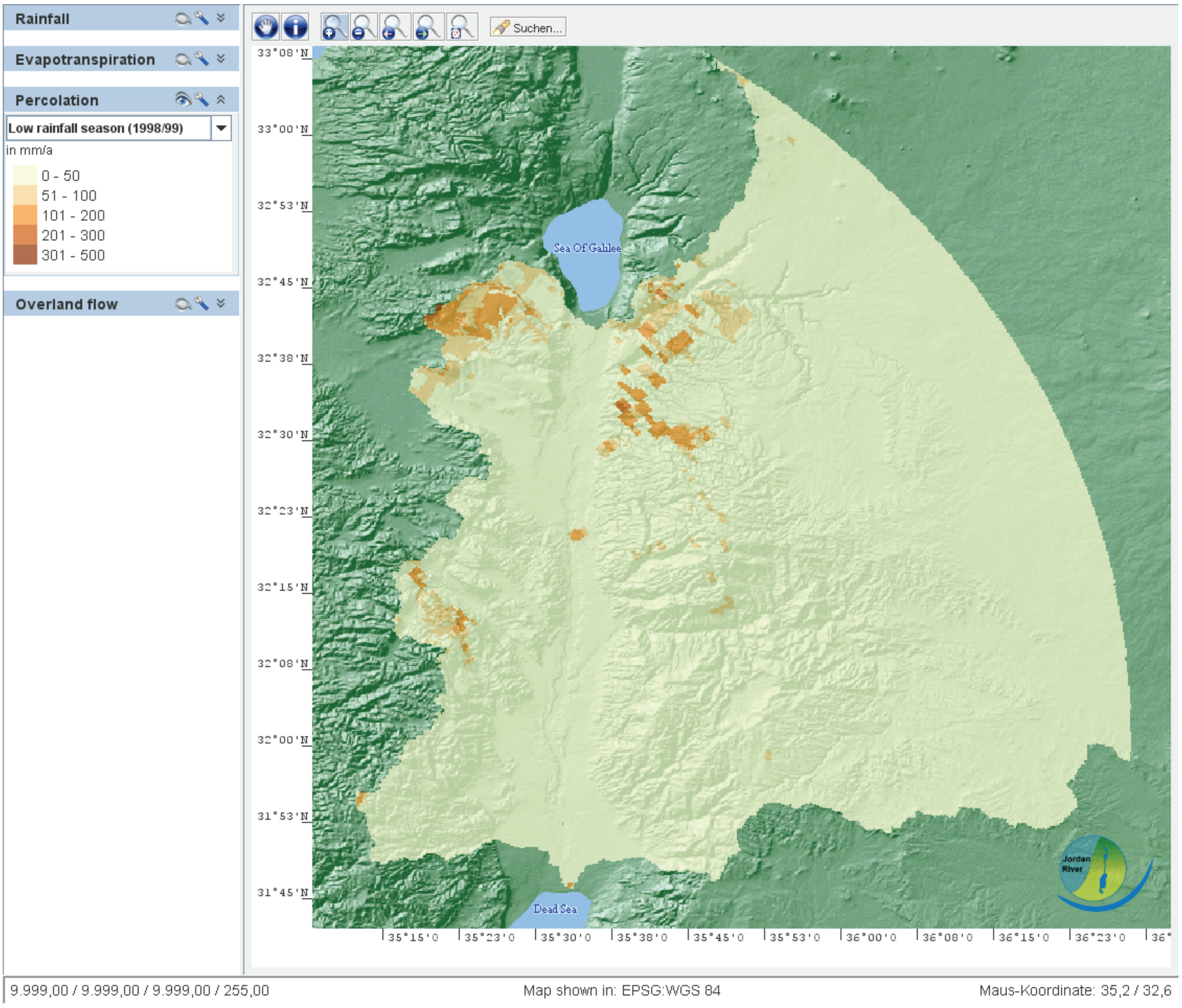

Figure 7 Amounts of percolation (mm/a) for the season 1998/99 (drought). The circular border of the values on the right indicates the effective range of the rainfall radar.

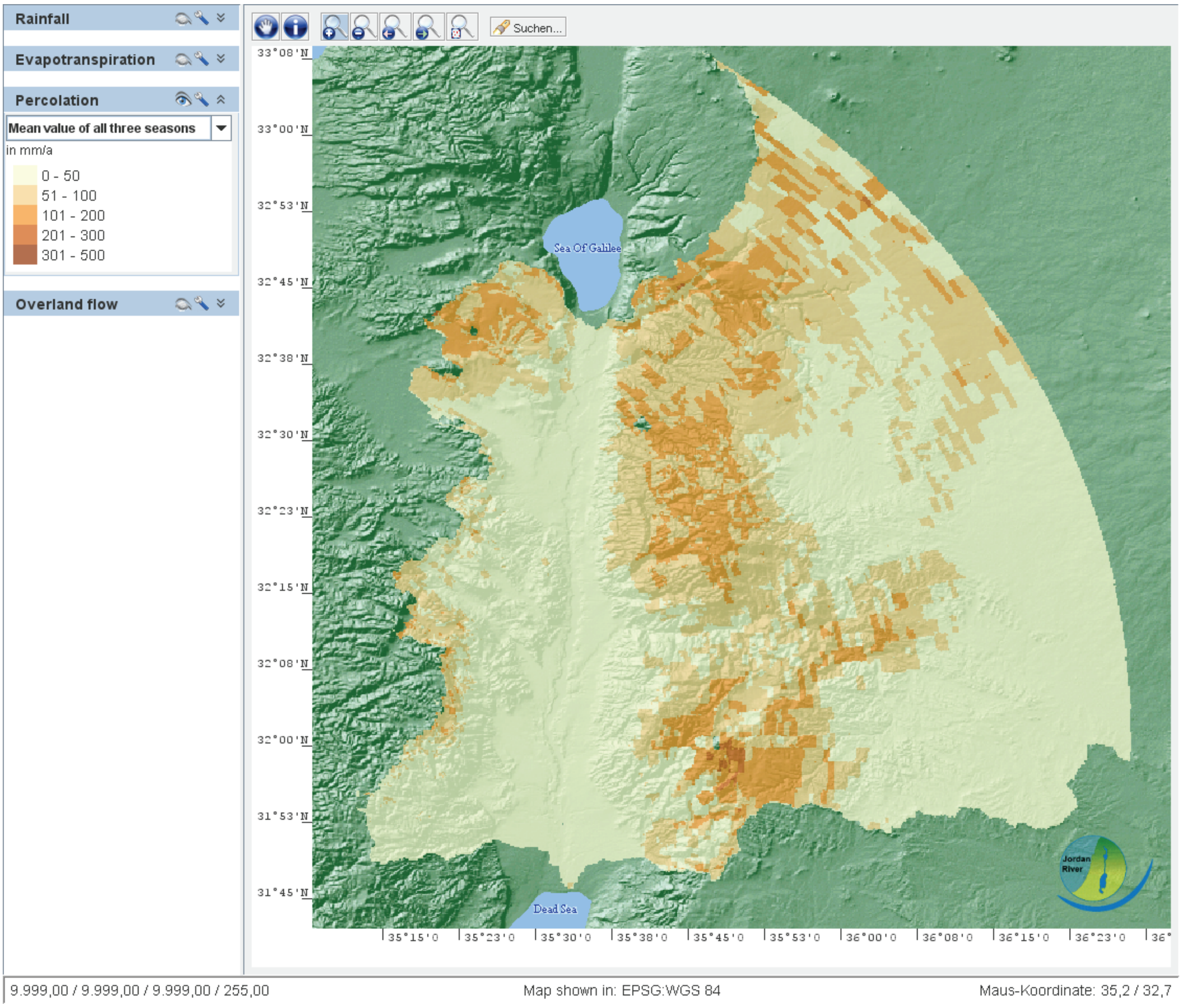

Figure 8 Average amounts of percolation (mm/a) for the three seasons 1991/92, 1998/99, 2002/03. The circular border of the values on the right indicates the effective range of the rainfall radar.

3.4 Water balance component - Overland flow

The amounts of overland flow for the season 1991/92 can be seen in Figure 9, the amounts for the season 1998/99 and the season 2002/03 in Gunkel & Lange (2012), and the mean amounts for all three seasons in Figure 10.

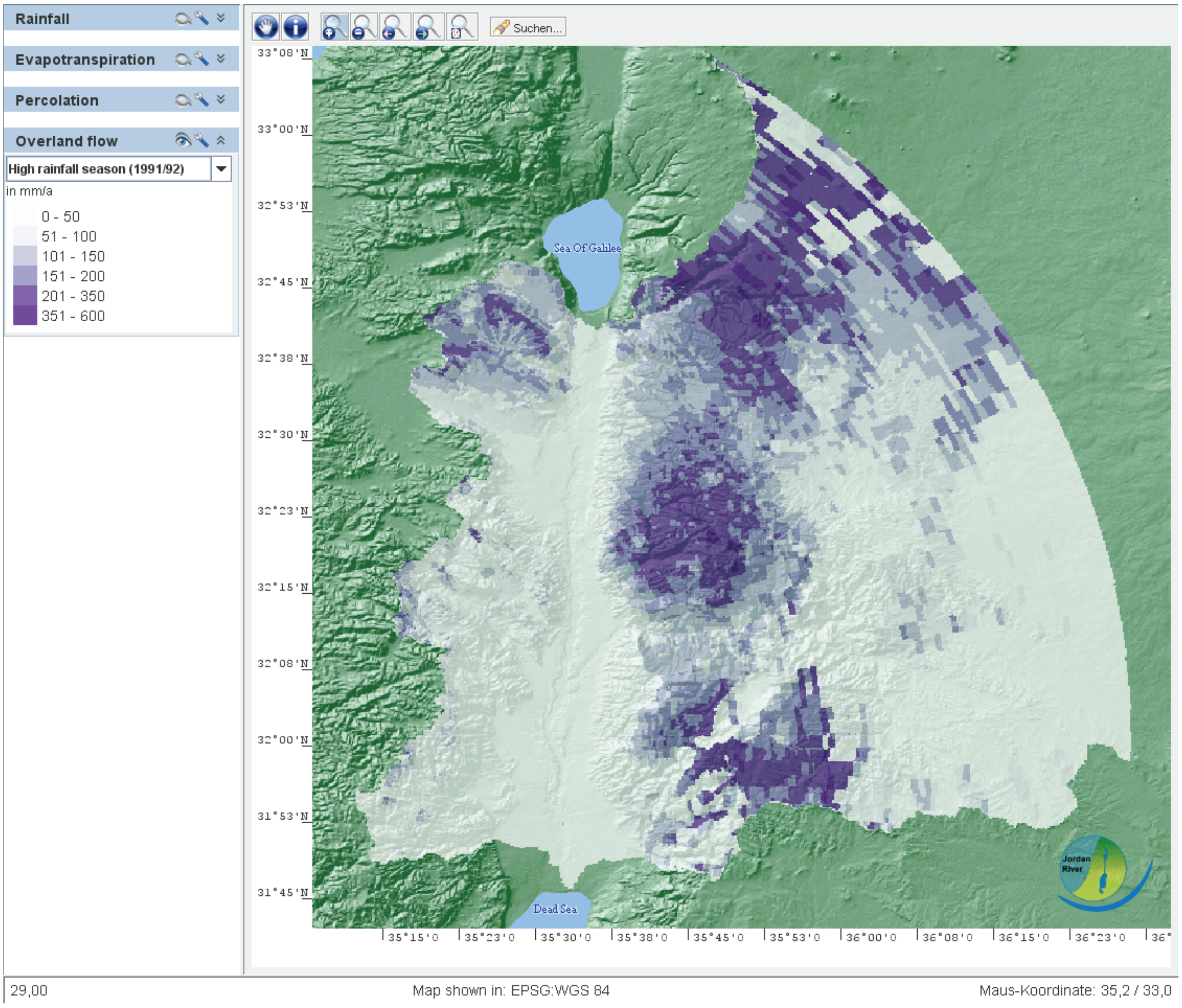

Figure 9 Amounts of overland flow (mm/a) for the season 1991/92 (wet extreme). The circular border of the values on the right indicates the effective range of the rainfall radar.

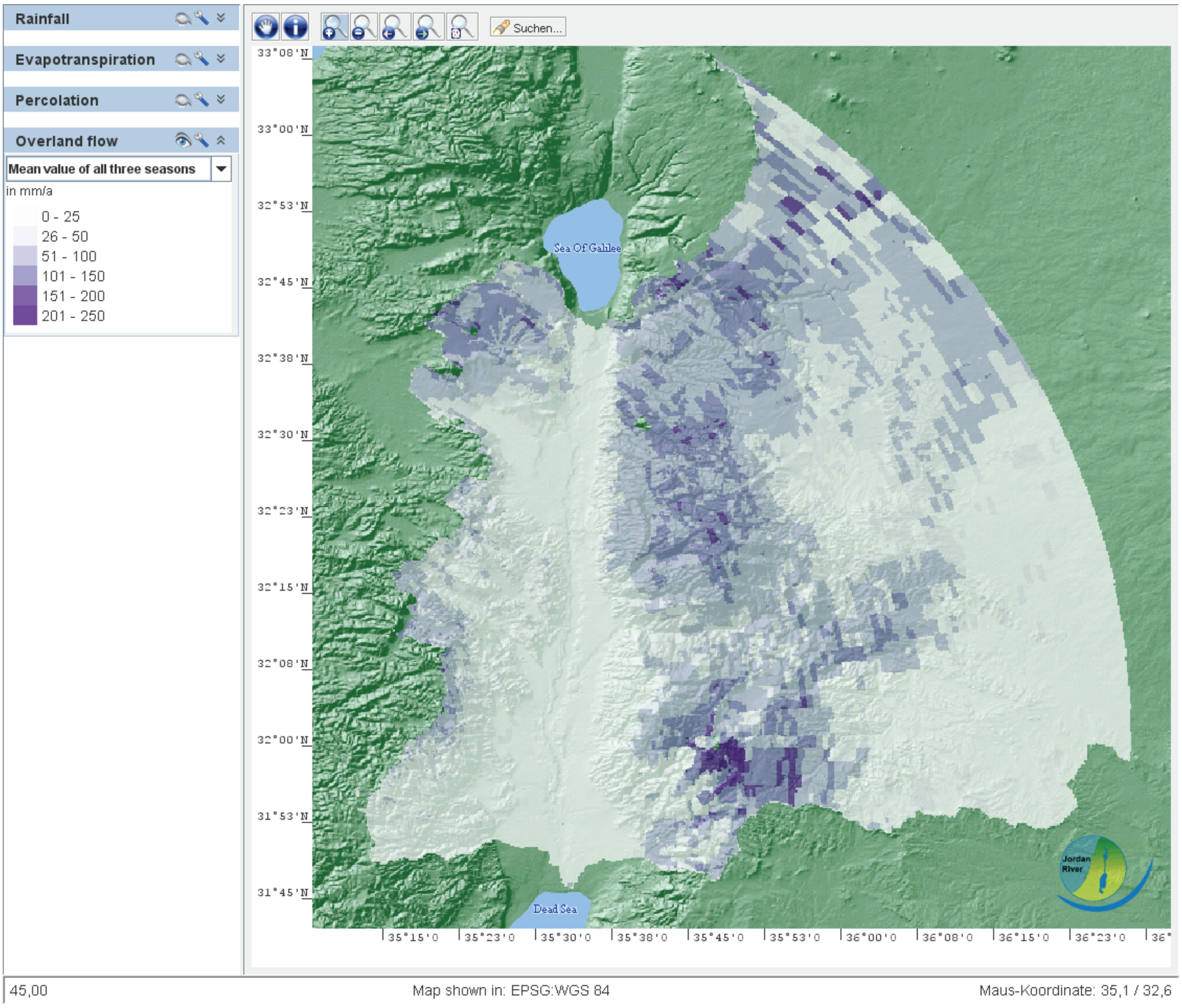

Figure 10 Average amounts of overland flow (mm/a) for the three seasons 1991/92, 1998/99, 2002/03. The circular border of the values on the right indicates the effective range of the rainfall radar.

3.5 Water balance component - Wadi runoff

The amounts of wadi runoff for the season 1991/92 can be seen in Figure 11, the amounts for the season 1998/99 in Figure 12, the amounts for the season 2002/03 in Figure 13, and the mean amounts for all three seasons in Figure 14.

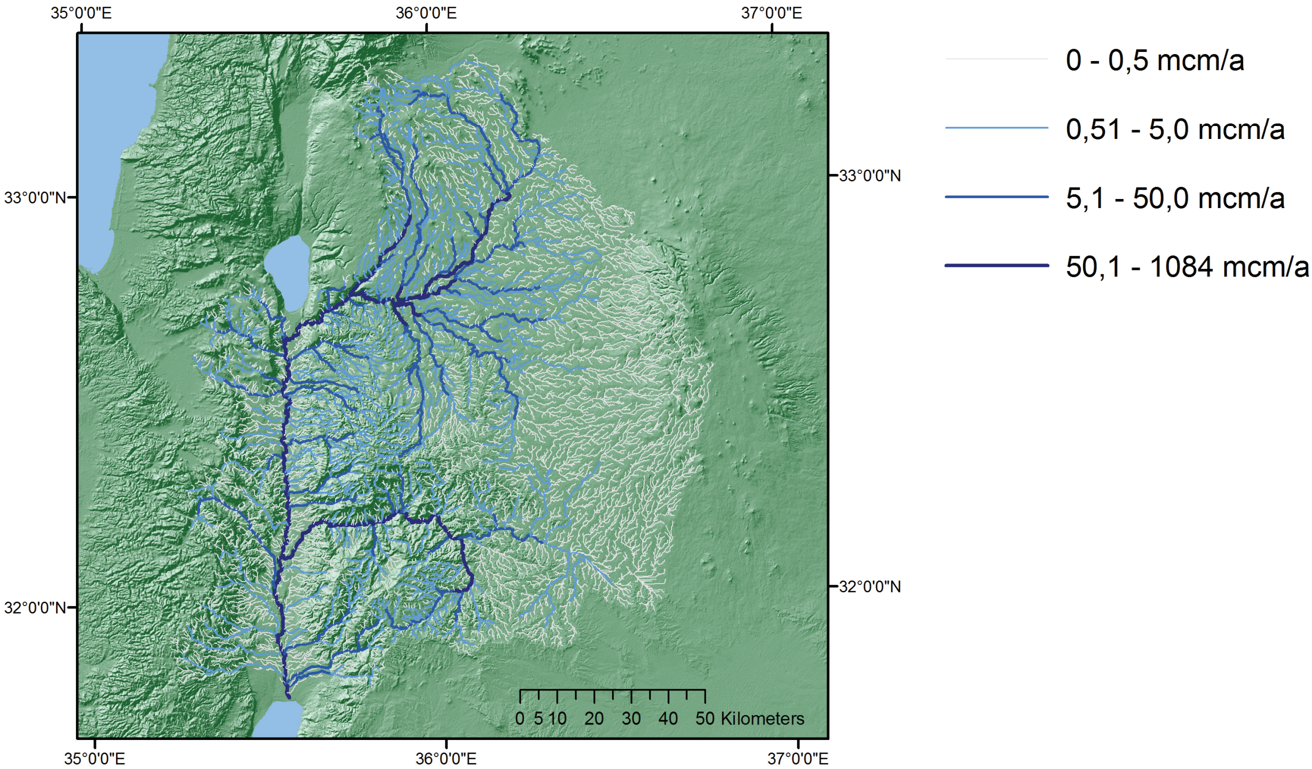

Figure 11 Amounts of wadi runoff (MCM/a) for the season 1991/92 (wet extreme).

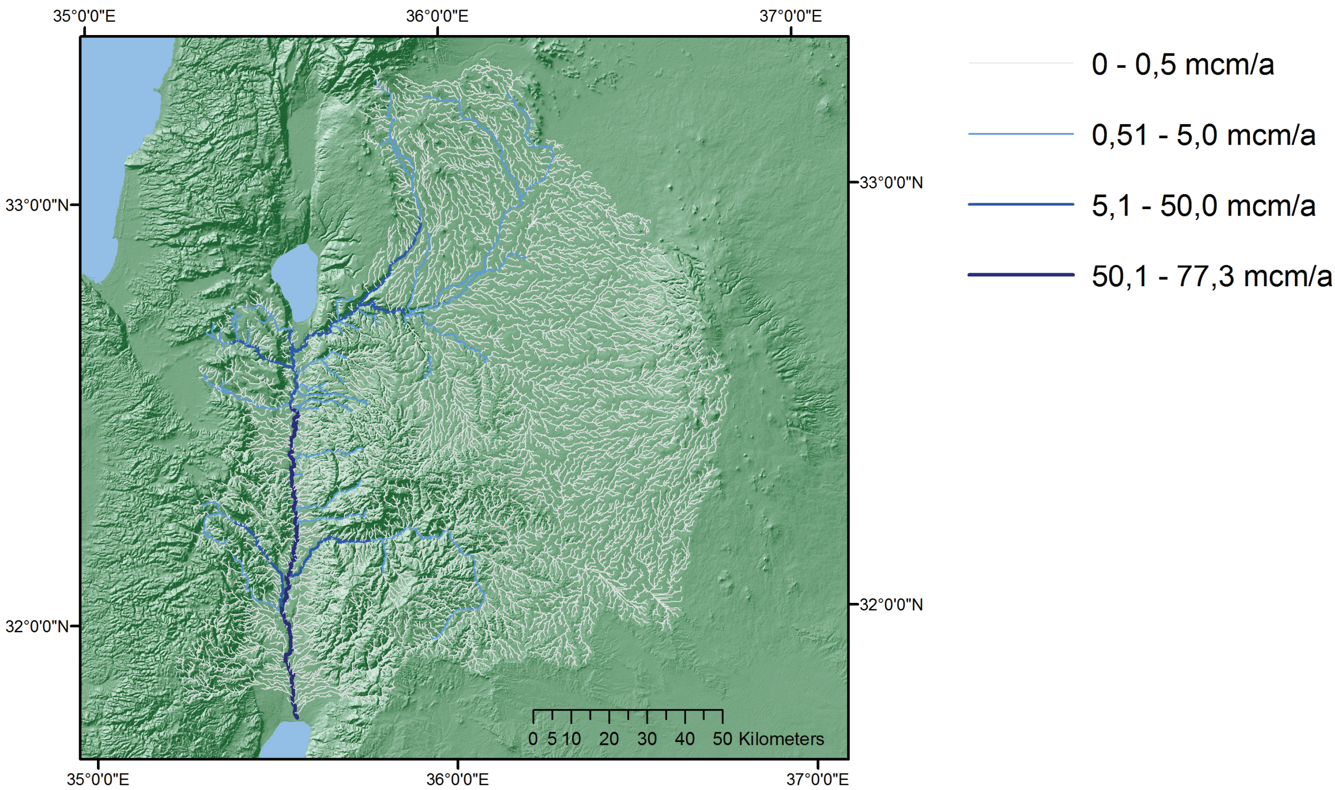

Figure 12 Amounts of wadi runoff (MCM/a) for the season 1998/99 (drought).

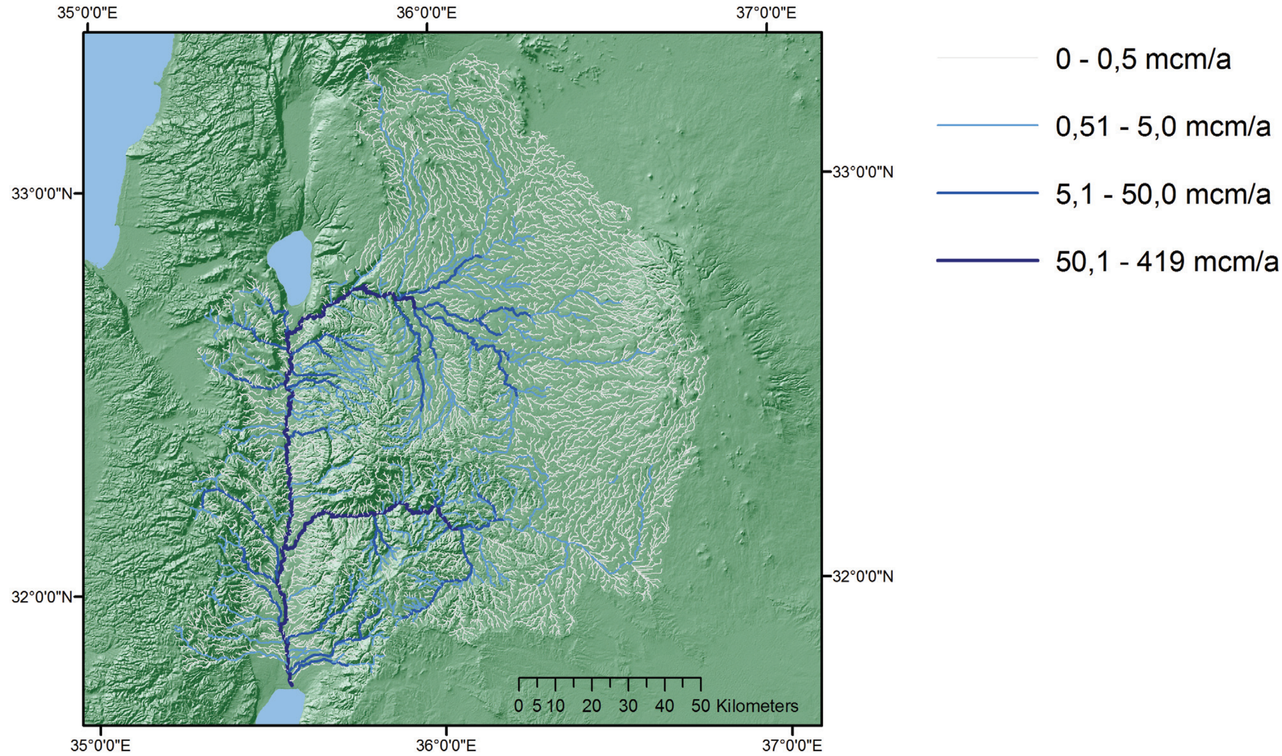

Figure 13 Amounts of wadi runoff (MCM/a) for the season 2002/03 (average rainfall season).

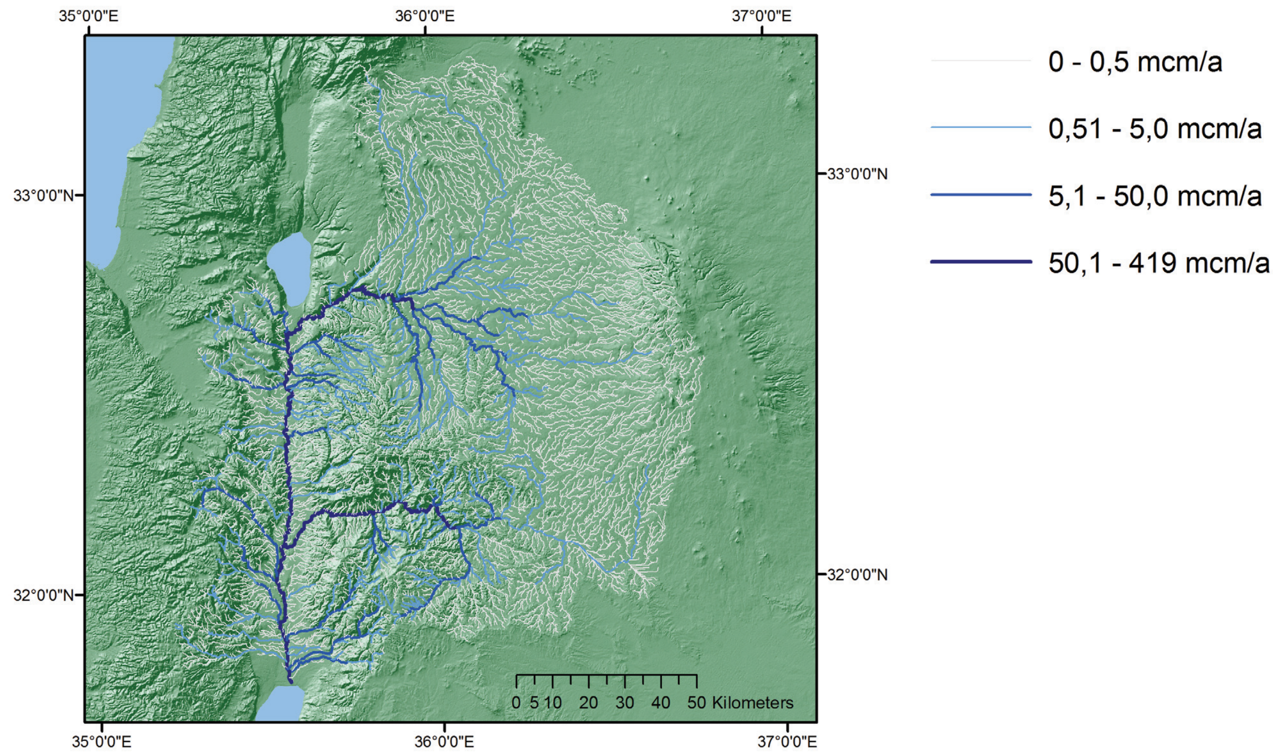

Figure 14 Mean amounts of wadi runoff (MCM/a) for all three seasons (1991/92, 1998/99, 2002/03)

3.6 New water source – Urban rainwater harvsting

Maximum potentials of U-RWH in the sub basins of the LJRB for the wet extreme season of 1991/92 can be seen in Figure 15, for the drought and average seasons of 1998/99 and 2002/03 in the annexed poster presented at the Final Conference of the GLOWA Jordan River Project in Limassol, Cyprus, 5-7 September 2011. The maximum potential of U-RWH for each season in MCM/a in the sub basins of the LJRB are showed in Table 1.

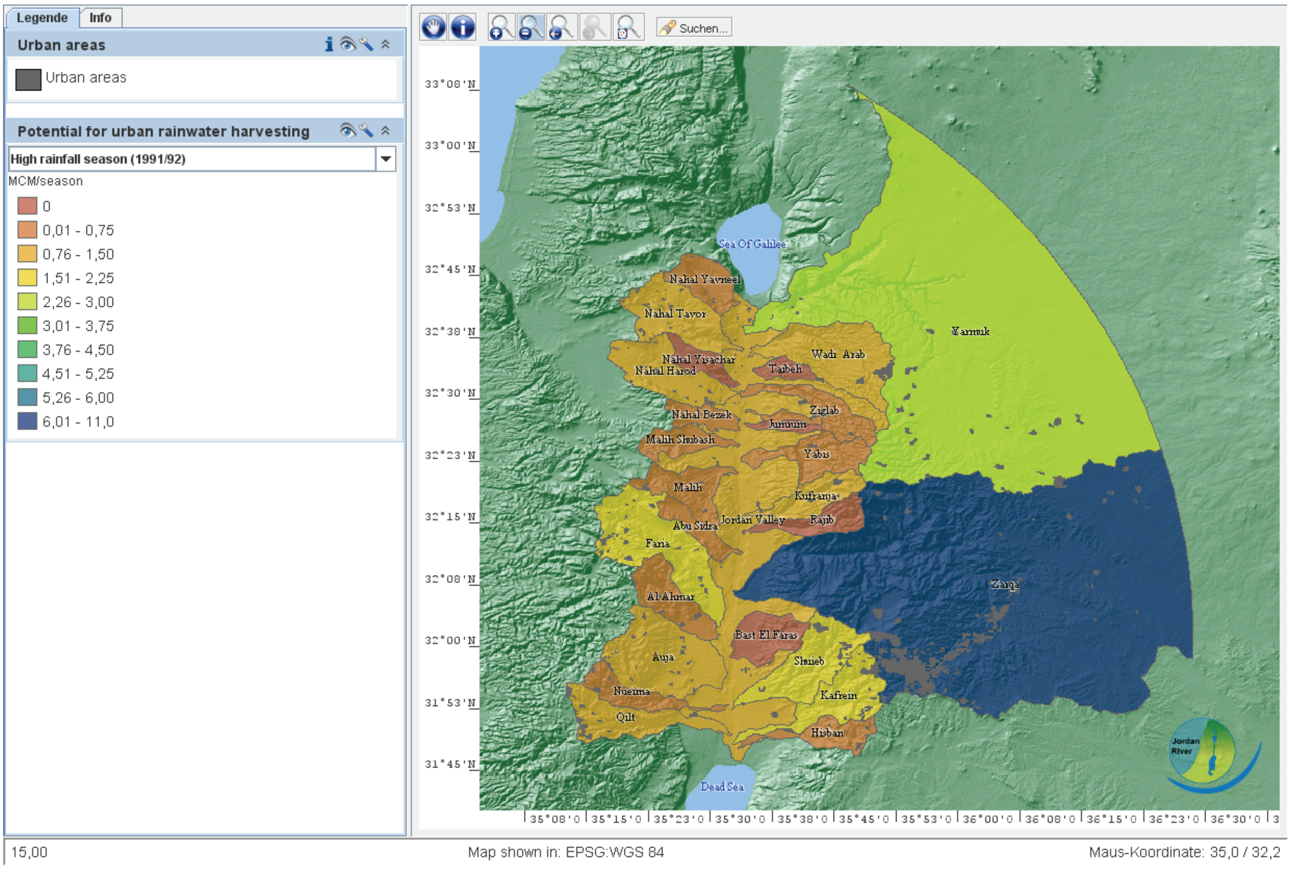

Figure 15 Maximum potentials of U-RWH (MCM/a) in the sub basins of the LJRB for the wet extreme season of 1991/92.

Table 1 Maximum potential of U-RWH (MCM/a) in the sub basins of the LJRB calculated for the three seasons: wet extreme (1991/92), drought (1998/99), average (2002/03).

		U-RWH Potential [MCM/a]					U-RWH Potential [MCM/a]		
	Catchment	**wet season**	**drought**	**Average**		**Catchment**	**wet season**	**drought**	**average**
Western Tributaries	Yavneel	0.49	0.18	0.38	Eastern Tributaries	Yarmuk	2.90	0.12	2.26
	Tavor	1.42	0.49	1.03		Arab	1.20	0.03	0.90
	Yisachar	0.07	0.02	0.06		Taibeh	0.01	0.00	0.01
	Harod	0.93	0.23	0.68		Ziglab	0.33	0.03	0.29
	Bezek	0.16	0.02	0.10		Ziad	0.14	0.02	0.11
	Malih Shubash	0.12	0.02	0.10		Jumrum	0.00	0.00	0.00
	Malih	0.49	0.10	0.32		Yabis	0.26	0.04	0.20
	Abu Sidra	0.11	0.02	0.07		Kufranja	0.76	0.12	0.51
	Faria	1.86	0.61	1.70		Rajib	0.00	0.00	0.00
	Al Ahmar	0.44	0.13	0.49		Zarqa	10.95	0.57	5.04
	Auja	0.93	0.18	0.82		Bast El Faras	0.00	0.00	0.00
	Nueima	0.29	0.09	0.23		Shuieb	2.18	0.08	1.61
	Qilt	1.32	0.58	1.42		Kafrein	1.94	0.08	1.43
	Jordan Valley	1.49	0.22	1.13		Hisban	0.44	0.01	0.37
	Sum	**10.13**	**2.90**	**8.52**		**Sum**	**21.09**	**1.09**	**12.72**
	Total Sum	**31.23**	**3.99**	**21.24**					

3.7 New water source – Rural rainwater harvesting

Maps on the maximum R-RWH potentials for the hillside conduit system technique on slopes > 10 % and the microcatchment systems on slopes < 5% during the drought season 1998/99 are showed in annexed poster presented at the Final Conference of the GLOWA Jordan River Project in Limassol, Cyprus, 5-7 September 2011. The results in MCM/a for the seasons 1998/99 and 2002/03 are showed in Table 2.

Table 2 Maximum R-RWH potentials (MCM/a) in the sub basins of the LJRB.

			Average season (2002/03)	Drought (1998/99)
	Subbasin	Size	Hillslope runoff	Hillslope runoff
		km²	*MCM/season*	*MCM/season*
Western Side Wadis	Yavne'el	101	7	5
	Tavor	207	14	13
	Yisachar	64	2	0
	Harod	192	9	3
	Bezek	60	1	0
	Malih Shubash	85	4	0
	Malih	129	4	0
	Abu Sidra	67	1	0
	Faria	332	16	7
	Al'Ahmar	139	9	2
	Auja	312	13	1
	Nueima	96	2	0
Eastern Side Wadis	Qilt	172	4	1
	Arab	275	26	4
	Taibeh	40	3	3
	Ziglab	115	12	3
	Ziad	21	2	0
	Jumrum	26	2	0
	Yabis	138	7	2
	Kufranja	113	4	2
	Rajib	94	2	1
	Bast el Faras	121	1	0
	Shuieb	218	17	0
	Kafrein	185	24	0
	Hisban	98	8	0
	TOTAL		192	47

4 Key messages

- The showed information is only representative for the investigated seasons, but show the entire present day climatic variablity in the region.
- The results feature the non-linear behaviour of (semi-)arid systems that is related to temporal and spatial variability of water resources in dry regions.
- In the LJRB, rainfall variablitiy strongly amplifies within the hydrological cycle.
- Overland flow may be used by rainwater harvesting techniques like microcatchment systems or hillside conduit systems.
- Wadi recharge into alluvial aquifers can artificially be increased (managed aquifer recharge)
- Basin averages of seasonal water balance components ranged between 65 and 489 mm (rainfall), 53 and 270 mm (evapotranspiration), 7 and 87 mm (overland flow), 4 and 129 mm (percolation); all values comprise enormous spatial variability.
- The total R-RWH potential for the LJRB varies from season to season: In an average rainfall year 195 MCM can be harvested, in a dry year only 48 MCM. (not including Yarmuk and Zarqa basins, neither runoff generated in the Jordan Valley itself).
- To minimize downstream effects, R-RWH should be concentrated to areas not feeding important reservoirs. For water management downstream effects and the high temporal variability of R-RWH must be considered.

5 Maps and data access

All maps, also the ones not showed here, can be seen at the digital GLOWA Jordan River atlas (see at http://tobias-lib.uni-tuebingen.de/portal/glowa) and the data accessed by contacting the author of correspondance.

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Annex

Poster presented during the the Final Conference of the GLOWA Jordan River Project in Limassol, Cyprus, 5-7 September 2011