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P.R. van Oel

A.Y. Hoekstra

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The green and blue water footprint of paper products: Methodological considerations and quantification

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THE GREEN AND BLUE WATER FOOTPRINT OF PAPER PRODUCTS: METHODOLOGICAL CONSIDERATIONS AND QUANTIFICATION

P.R. VAN OEL[1]

A.Y. HOEKSTRA[2]

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[1] ITC, University of Twente, Enschede, The Netherlands, Pieter van Oel, oel@itc.nl

[2] Water Engineering and Management Department, University of Twente, Enschede, The Netherlands, a.y.hoekstra@utwente.nl

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Summary

For a hardcopy of this report, printed in the Netherlands, an estimated 200 litres of water have been used. Water is required during different stages in the production process, from growing wood to processing pulp into the final consumer product. Most of the water is consumed in the forestry stage, where water consumption refers to the forest evapotranspiration. The water footprint during the manufacturing processes in the industrial stage consists of evaporation and contamination of ground- and surface water. In this report we assess water requirements for producing paper products using different types of wood and in different parts of the world. We quantify the combined green and blue water footprint of paper by considering the full supply chain; we do not include the grey water footprint in this study.

The water footprint of printing and writing paper is estimated to be between 300 and 2600 m^3/ton (2-13 litres for an A4 sheet). These figures account for the paper recovery rates as they currently are. The exact amount depends on the sort and origin of the paper used for printing. Without recovery, the global average water footprint of paper would be much larger; by using recovered paper an estimated 40% is saved globally. Further saving can be achieved by increasing the recovery percentages worldwide. For countries with a low recovered paper utilization rate a lot of room for reduction still remains. Some countries such as the Netherlands, Spain and Germany already use a lot of recovered paper. In addition, the global water footprint of paper can be reduced by choosing production sites and wood types that are more water-efficient.

The findings presented in this report can be helpful in identifying the opportunities to reduce water footprints of paper consumption. This report also shows that the use of recovered paper may be very helpful in reducing water footprints.

1. Introduction

Forests are renewable resources that are key to the production of paper, since the main ingredient of paper is wood pulp (cellulose). Next to their importance for paper, forests are important for the production of other goods, such as timber and firewood, the conservation of biodiversity, the provision of socio-cultural services and carbon storage. Forests also play a vital role in catchment hydrology. Deforestation and afforestation affect hydrological processes in a way that may directly influence water availability. It is for instance well established that a reduction in runoff is expected with afforestation on grasslands and shrublands (e.g. Fahey and Jackson, 1997; Farley et al., 2005; Jackson et al., 2005; Wilk and Hughes, 2002).

Large amounts of freshwater are required throughout the supply chain of a product until the moment of consumption. For quantifying this amount, the water footprint concept can be used (Hoekstra and Chapagain, 2007b; 2008). The water footprint of a product is defined as the total amount of freshwater that is needed to produce it. The water footprint can contain green, blue and grey components. The green component is the volume of water evaporated from rainwater stored in or on the vegetation or stored in the soil as soil moisture. The blue component refers to evaporated surface and ground water. The grey component is the volume of polluted ground- and surface water. An increasing number of publications on virtual-water trade and water footprint of consumer products has emerged in recent years (Chapagain and Hoekstra, 2007; 2008; Chapagain et al., 2006a; 2006b; Gerbens-Leenes et al., 2009; Hoekstra and Chapagain, 2007a; 2007b; 2008; Hoekstra and Hung, 2005; Liu and Savenije, 2008; Liu et al., 2008; 2007; Ma et al., 2006; Van Oel et al., 2009). So far, the water footprint of paper products has not been studied in enough detail to reflect on its claims on water resources. There are several product-specific issues that have to be addressed in order to come to a fair assessment of the water footprint of paper products. In this report the main issues are addressed and some ways to deal with them are proposed and discussed.

In this report, a method for determining the water footprint of paper products at the national level is proposed that takes into account both the forestry and the industrial stage of the production process. The scope is limited to a study of consumptive water use – considering both the green and blue water footprint. We do not consider the grey water footprint in this report. First, we estimate the water footprint of paper products produced using pulp from the main pulp producing countries in the world. We take into account the use of recovered paper. Second, a method for the quantification of the water footprint of paper products that are consumed in a specific country is presented and applied for the Netherlands.

2. Method

2.1 Estimating the water footprint of paper products

The water footprint during the forestry stage contains both a green and blue component. These two components cannot easily be determined separately as trees use rainfall water and tap from groundwater resources simultaneously. Therefore, in the scope of this study, we estimate the green and blue water footprint of paper products as a total sum. During the industrial stage there is only a blue water footprint. The water footprint of a paper product p (expressed in m^3/ton) is estimated as follows:

$$WF[p] = WF_{forestry}[p] + WF_{industry}[p]$$

The water footprint of a paper product for the forestry stage is estimated as follows:

$$WF_{forestry}[p] = \left(\frac{ET_a + (Y_{wood} \times f_{water})}{Y_{wood}} \right) \cdot f_{paper} \times f_{value} \times (1 - f_{recycling})$$

in which ET_a is the actual evapotranspiration from a forest/woodland (m^3/ha/year), Y_{wood} the wood yield from a forest/woodland (m^3/ha/year), f_{water} the volumetric fraction of water in freshly harvested wood (m^3/m^3), f_{paper} the wood-to-paper conversion factor (i.e. the harvested volume needed to produce a metric ton of paper product (m^3/ton), f_{value} the fraction of total value of the forest which is associated with paper production (dimensionless) and $f_{recycling}$ the fraction of pulp derived from recycled paper (dimensionless). Note that the wood-to-paper conversion factor relates to the so-called product fraction (f_p, *mass/mass*) that is used in the standard calculation of a product water footprint (Hoekstra et al., 2009). The two parameters relate as follows:

$$f_{paper} = \frac{1}{f_p \times \rho}$$

with ρ being the density of harvested wood (ton/m^3).

The water footprint of a paper product for the industrial stage is estimated as follows:

$$WF_{industry}[p] = E + R + P$$

in which E is the evaporation in the production process (m^3/ton), R the water contained in solid residuals (m^3/ton) and P the water contained in products (m^3/ton).

Step 1: Estimating evapotranspiration (ET_a) by forest type and by country

There are several factors that influence evapotranspiration from forest biomes, including meteorological conditions, tree type and forest management. To get an overview of evapotranspiration from forests at the global level, use is made of two data sources that are both obtained from FAO GeoNetwork (Figure 1):

- The World's Forests 2000 (FAO, 2001): this dataset is based on 1992-93 and 1995-96 AVHRR data and gives global distribution of forest biomes at a resolution of 1 km. Five different forest types are distinguished: boreal (typical trees include pine, fir, and spruce), tropical (typical trees include eucalyptus), sub-tropical, temperate (typical trees include oak, beech and maple) and polar forest. Different forest types can be present in one country. For its low relevance, polar forests have been ignored.
- Annual actual evapotranspiration (FAO, 2009b): this dataset contains annual average values for the period 1961-1990 at a resolution of 5 arc minutes.

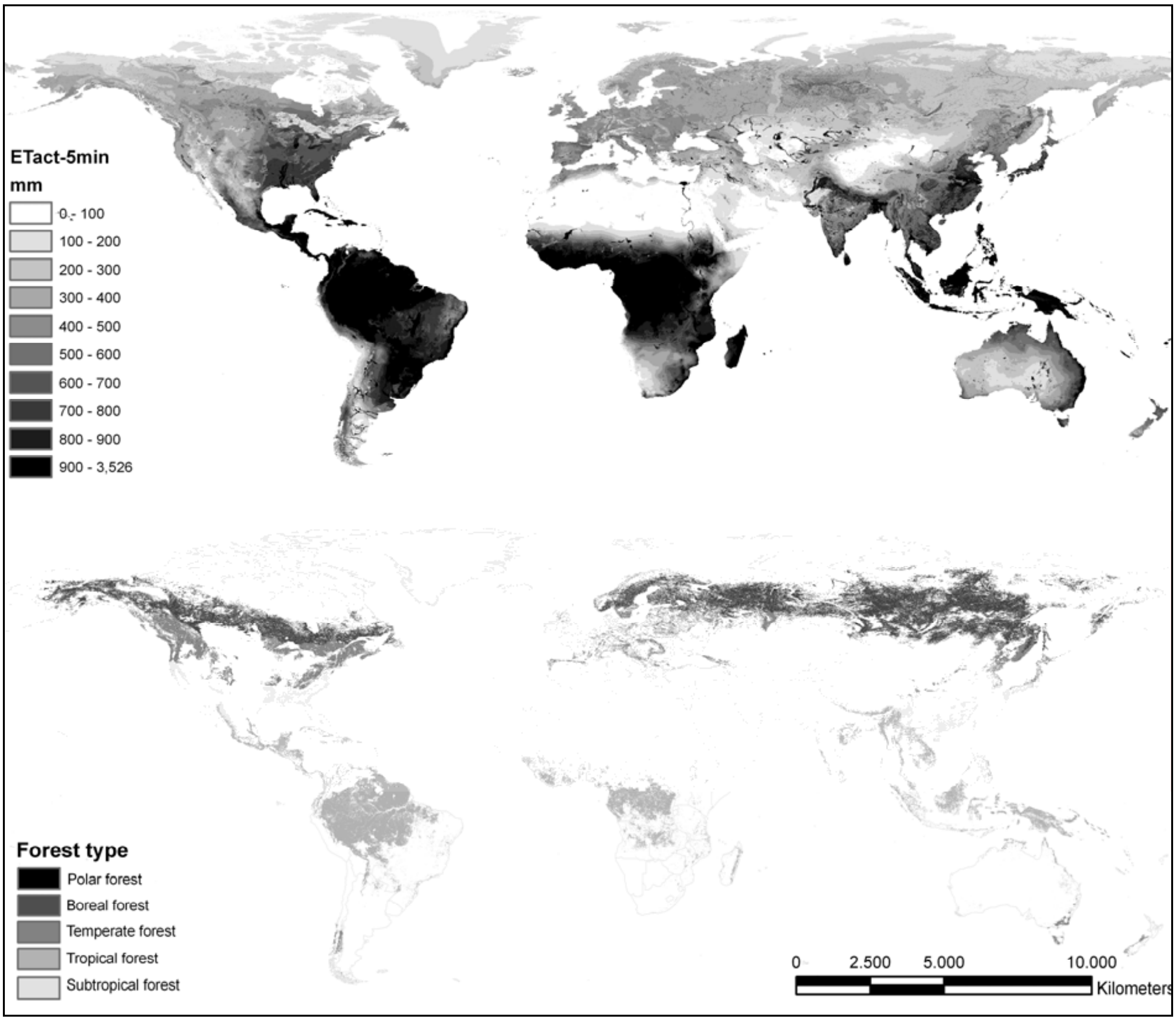

Figure 1. Top: annual actual evapotranspiration (FAO, 2009b). The dataset contains yearly values for global land areas for the period 1961-1990. Bottom: The World's Forests 2000 (FAO, 2001) This database is based on 1992-93 and 1995-96 AVHRR data.

With these data it is possible to obtain a rough estimate of annual evapotranspiration values for forests in most countries of the world. Country averages are determined by averaging all values of actual evapotranspiration in a country for all locations that are covered with closed forest. For calculating the water footprint of paper products, evapotranspiration values for the 22 main global producers of pulp (FAO, 2009a) are determined. Together, these countries produced 95% of globally produced pulp for the period 1998-2007. The locations from which wood is actually obtained remain unclear from statistics on pulp production. Therefore it is difficult to relate the right amount of evapotranspiration to the production of pulp. Due to a lack of detailed spatial information, in this study ranges of possible evapotranspiration values are presented, rather than estimates for actual forestry locations. Besides uncertainties on locations of origin within a producing country, also import from other countries may be important. Paper mills in Sweden, for example, use 75% of wood that originates from Sweden itself; the other 25% is imported from Latvia, Estonia and Lithuania (Gonzalez-Garcia et al., 2009). These pre-processing international trade flows are not taken into account in this study.

Table 1 shows the average annual evapotranspiration for the main pulp producing countries by forest type. If only one forest type exists in a country, only one value will be considered. If more than one forest type exists, the values of all forest types are given. For large countries covering several climatic zones, such as the USA, values of evapotranspiration may vary considerably.

Table 1. Contribution to annual pulp production and estimates for average actual annual evapotranspiration by forest type in the main pulp-producing countries.

Pulp producing country	Contribution to global pulp production*	Share of chemical pulp*	Average actual annual evapotranspiration by forest type (mm/year)**			
			Boreal	Temperate	Subtropical	Tropical
USA	29.5%	85%	278	516	635	1730
Canada	13.5%	52%	358	360	-	-
China	9.2%	11%	370	416	608	547
Finland	6.5%	60%	355	293	-	-
Sweden	6.3%	69%	345	318	-	-
Japan	5.9%	87%	-	637	725	-
Brazil	4.8%	93%	-	-	965	1048
Russia	3.3%	74%	310	362	-	-
Indonesia	2.4%	93%	-	-	-	1071
India	1.7%	37%	-	-	455	551
Chile	1.6%	86%	-	567	578	-
France	1.3%	67%	-	401	386	-
Germany	1.3%	44%	-	363	-	-
Norway	1.2%	26%	328	303	-	-
Portugal	1.0%	100%	-	512	502	-
Spain	1.0%	93%	-	547	527	-
South Africa	1.0%	72%	-	-	819	762
Austria	0.9%	76%	-	344	-	-
New Zealand	0.8%	45%	-	491	630	-
Australia	0.6%	50%	-	768	775	818
Poland	0.6%	76%	-	377	-	-
Thailand	0.5%	86%	-	-	-	636
Total	94.8%					

* Data source: annual averages for the period 1996-2005 based on FAOSTAT data (FAO, 2009a).
** Data sources: national averages estimates based on grid data from FAO (2001; 2009b).

Step 2: Estimating wood yield (Y_{wood})

For this study it has been assumed that the wood used for the production of wood pulp is harvested at a rate corresponding to the maximum sustainable annual yield from productive forests with wood production as its primary function. We will reflect upon this approach in the discussion section. Data on wood products are obtained from the Global Forest Resources Assessment 2005 (FAO, 2006). The estimates used in this study are presented in Table 2. Tree types are categorized into pine, eucalyptus and broadleaves. In this study the following assumptions are made for tree types in different forest biomes:

- Boreal forests yield pine
- Temperate forests yield broadleaves and pine
- Subtropical and tropical forests yield eucalyptus

Table 2. Wood yield estimates for the main pulp-producing countries.

Pulp producing country	Wood yield estimates (m^3/ha/year)*		
	Broadleaves	Eucalyptus	Pine
USA	7***	16***	6
Canada	7***		6**
China	6	6	4
Finland	7		6
Sweden	7**		8**
Japan	11	14	7**
Brazil	20	45	
Russia	7***		8***
Indonesia		19	
India		10	
Chile	22	26	19
France	7**	16**	9
Germany	7**		8**
Norway	7**		8**
Portugal	7**	16**	8**
Spain	7**	16**	8**
South Africa	11	23	
Austria	7**		8**
New Zealand	14	19**	15
Australia	14**	19	12
Poland	8		7
Thailand		14**	

* Data source: FAO (2006).

** Continental averages from available data are assumed.

*** European continental averages are used. In the case of Canada and the United States this is due to a lack of available data. For Russia, a European average is assumed to be more representative than the Asian continental average.

Step 3: Fraction of water in harvested wood (f_{water})

Generally this fraction is around 0.4 m^3 of water per m^3 of freshly harvested wood (Gonzalez-Garcia et al., 2009; NCASI, 2009). A large part of the water may be returned to surface or ground water during the industrial manufacturing process. It is however removed from the forest area and should therefore be accounted for in the water footprint in the forestry stage.

Step 4: Wood-to-paper conversion factors (f_{paper})

This is the amount of wood needed to produce a certain mass of paper product (m^3/ton). Estimates for important products are obtained from the UNECE conversion factors report (UNECE/FAO, 2010). The main conversion factors are summarized in Table 3. The product categories used in this study are based on the categories as used in the ForestSTAT database (FAO, 2009a). For different kinds (and qualities) of paper different types of pulp are used. The pulp differs according to the type of pulping technique that is applied. In this study no differences are made for different tree types.

Table 3. Wood-to-paper conversion factors.

Product	FAO product code (FAO, 2009a)	ITC product group codes used (ITC, 2006)	Conversion factors based on UNECE/FAO (2010) (m^3/ton)
Mechanical Wood Pulp	1654	2512	2.50
Semi-Chemical Wood Pulp	1655	25191	2.67
Chemical Wood Pulp	1656	2514, 2515, 2516	4.49
Dissolving Wood Pulp	1667	2513	5.65
Recovered Paper	1669	2511	
Newsprint	1671	6411	2.87
Printing & Writing Paper	1674	6412, 6413	3.51
Other Paper & Paperboard	1675	6414, 6415, 6416, 6417, 6419, 642	3.29

Step 5: Estimating the fraction of total value of the forest associated with paper production (f_{value})

Forests generally serve multiple functions, one of which may be the production of paper products. Others may be the production of timber, biodiversity conservation and carbon storage. Therefore, not all evapotranspiration from a forest should necessarily be attributed to the production of paper products. A value fraction (Hoekstra et al., 2009) could be determined to allocate the amount of water to be allocated to the production of wood pulp for a forest with *n* functions, including the production of wood pulp:

$$f_{value}[pulp] = \frac{value[pulp]}{\sum_{i=1}^{n} value[i]}$$

In this study it is assumed that paper is produced from forests that have wood production as the primary function and for which annual growth is equal to annual harvest, so we assume the value fraction to be equal to 1. We will come back to this issue in the discussion section.

Step 6: Estimating the fraction of pulp derived from recovered paper ($f_{recycling}$)

Recycling is an important factor for the water footprint, because fully recycled paper avoids the use of fresh wood and thus nullifies the water footprint in the forestry stage. When more recovered paper is used, the overall water footprint will decrease. On average an estimated 41% of al produced pulp is obtained from recycled paper (FAO/CEPI, 2007; UNECE/FAO, 2010), with large differences between producers using no recycled paper at all to producers that achieve relatively high percentages. We obtained the ‘recovered paper utilization rates’ for the main pulp producing countries from FAO/CEPI (2007). The ‘recovered paper utilization rate’ is the amount of recovered paper used for paper and paperboard as a percentage of paper and paperboard production. Losses in repulping of recovered paper are estimated to be between 10 and 20 percent (FAO/CEPI, 2007). In this study, 15 percent is used for all countries. The values used in this study are summarized in Table 4. The product categories for which recycling is taken into account are only the consumer product categories (i.e. newsprint, 'printing & writing paper' and 'other paper & paperboard'), since these are the only categories for which it is actually used.

Table 4. Recovered paper utilization rates and $f_{recycling}$ for the main pulp-producing countries.

Country	Recovered paper utilization rate*	Fraction of pulp derived from recycled paper ($f_{recycling}$)**
USA	0.37	0.31
Canada	0.24	0.20
China	0.42*	0.36
Finland	0.05	0.04
Sweden	0.17	0.14
Japan	0.61	0.52
Brazil	0.40	0.34
Russia	0.42***	0.36
Indonesia	0.42***	0.36
India	0.42***	0.36
Chile	0.42	0.36
France	0.60	0.51
Germany	0.67	0.57
Norway	0.22	0.19
Portugal	0.21	0.18
Spain	0.85	0.72
South Africa	0.42***	0.36
Austria	0.46	0.39
New Zealand	0.25	0.21
Australia	0.64	0.54
Poland	0.36	0.31
Thailand	0.59	0.50
Average of main pulp producing countries	0.42	0.36
Netherlands	0.70	0.60

* Data source: FAO/CEPI (2007).

** 85% of recovered paper utilization rate assumed due to loss in processing.

*** When no data are available for the individual country, the average of the other countries is used.

<u>Step 7: Estimating the water footprint of paper products in the forestry stage</u>

For a quantification of the water footprint of paper products in the forestry stage, estimates for the main pulp producing countries are made, as listed in Table 1.

<u>Step 8: Estimating the water footprint of paper products in the industrial stage</u>

The water footprint of paper products in the industrial stage of production is estimated based on the case of the USA, considering the country's paper and pulp production sector as a whole (NCASI, 2009). The USA is the largest producer of paper pulp and is assumed to be representative for the global paper industry. In this study no comparison is made between different techniques and processes that may be used in producing pulp.

2.2 Estimating the water footprint of paper consumption in a country

Many countries strongly depend on imports of pulp and paper. For those countries it is relevant to know the water footprints of the imported products and where these water footprints are located. This will be shown in a case study for the Netherlands. As a basis, we use data on the annual production, import, export and consumption of paper for the Netherlands as shown in Table 5.

Table 5. Annual production, import, export and consumption for the Netherlands for the period 1996-2005.

Product	Pulp	Newsprint	Printing & writing paper	Other paper & paperboard
FAO code	1654-56, 1667	1671	1674	1675
Production (ton/year)*	125350	387700	895400	1987200
Import quantity (ton/year)*	1132860	476540	1267890	1498200
Export quantity (ton/year)*	322340	259480	1143450	1417900
Consumed (ton/year)	935870	604760	1019840	2067500

* Source: ForestStat (FAO, 2009a).

A weighted average for all import partners is made for a few different paper products, similar to the way it is done by van Oel et al. (2009) and Hoekstra et al. (2009). Data on imports specified by trade partner are used from the International Trade Centre (ITC, 2006). Table 3 shows the product categories used for estimating the water footprints of imported paper products. The average water footprint WF^* of a paper product p consumed in the Netherlands (NL) is estimated by assuming that:

$$WF^*[NL,p]=\frac{P[NL]\times WF[NL,p]+\sum_{c=1}^{m}\left(I[c]\times WF[c,p]\right)}{P[NL]+\sum_{c=1}^{m}I[c]}$$

in which $WF[NL,p]$ is the water footprint of paper product p produced in the Netherlands using Dutch pulp; $WF[c,p]$ the water footprint of paper product p produced in the Netherlands using pulp from country c; $P[NL]$ the production of wood equivalents in the Netherlands, and $I[c]$ the import of wood equivalents into the Netherlands from country c. The various sorts of pulp produced in and imported into the Netherlands are expressed in wood equivalents using the conversion factors as shown in Table 3. The assumption here is that paper products are based on domestic and imported pulp according to the ratio of domestic pulp production to pulp import. On the Dutch market, in the period 1996-2005, 6% of the available pulp (expressed in terms of wood equivalents) had domestic origin; the remaining 94% was imported.

3. Results

3.1 The water footprint of paper products

The evapotranspiration per volume of harvested wood for the main pulp producing countries is shown in Table 6. The water footprint of paper products is shown in Tables 7-9. Country-specific recycling percentages are incorporated in these values. The lowest estimate for printing & writing paper is 321 m^3/ton (eucalyptus from subtropical biome in Spain) and the highest value is 2602 m^3/ton (eucalyptus from tropical biome in the USA), corresponding to 2 and 13 litres per sheet of standard A4 copy paper respectively. If no recovered paper would have been used, these values would become 753 m^3/ton (eucalyptus from subtropical biome in Brazil) for the lower estimate and the higher estimate would be 3880 m^3/ton (eucalyptus from subtropical biome in China). For one sheet of A4 copy paper this means 4 and 19 litres respectively.

Table 6. Water footprint of harvested wood for the main pulp-producing countries.

	Water footprint for different trees and places of origin (m^3/m^3)				
Pulp producing country	Pines from Boreal biome	Pines from Temperate biome	Broadleaves from Temperate biome	Eucalyptus from Subtropical biome	Eucalyptus from Tropical biome
USA	463	860	752	397	1081
Canada	597	600	525		
China	891	1001	693	1105	995
Finland	592	488	451		
Sweden	413	381	463		
Japan		859	571	527	
Brazil				214	233
Russia	371	434	528		
Indonesia					564
India				455	551
Chile		298	262	222	
France		446	584	241	
Germany		435	529		
Norway	393	363	442		
Portugal		613	746	314	
Spain		655	797	329	
South Africa				356	331
Austria		412	501		
New Zealand		335	351	338	
Australia		662	549	415	438
Poland		539	459		
Thailand					463

Table 7. Water footprint of newsprint (m^3/ton), taking into account country-specific recovered paper utilization rates.

Country	Pine from boreal biome	Pine from temperate biome	Broadleaf from temperate biome	Eucalyptus from subtropical biome	Eucalyptus from tropical biome
USA	912	1692	1479	781	2127
Canada	1363	1371	1199		
China	1648	1852	1282	2045	1840
Finland	1626	1342	1239		
Sweden	1015	935	1138		
Japan		1187	789	729	
Brazil				406	441
Russia	687	802	976		
Indonesia					1043
India				842	1019
Chile		551	483	410	
France		627	822	339	
Germany		537	654		
Norway	917	847	1030		
Portugal		1446	1759	740	
Spain		522	635	262	
South Africa				659	613
Austria		720	876		
New Zealand		757	793	763	
Australia		866	718	543	573
Poland		1073	914		
Thailand					662

Table 8. Water footprint of 'printing & writing paper' (m^3/ton), taking into account country-specific recovered paper utilization rates.

Country	Pine from boreal biome	Pine from temperate biome	Broadleaf from temperate biome	Eucalyptus from subtropical biome	Eucalyptus from tropical biome
USA	1115	2069	1809	955	2602
Canada	1667	1676	1466		
China	2015	2266	1568	2501	2250
Finland	1988	1641	1515		
Sweden	1241	1144	1392		
Japan		1452	965	891	
Brazil				497	540
Russia	840	981	1193		
Indonesia					1275
India				1029	1246
Chile		674	591	502	
France		766	1005	415	
Germany		657	799		
Norway	1121	1036	1260		
Portugal		1769	2151	905	
Spain		638	776	321	
South Africa				806	749
Austria		881	1072		
New Zealand		925	969	933	
Australia		1060	878	665	701
Poland		1312	1118		
Thailand					809

Table 9. Water footprint of 'other paper & paperboard' (m^3/ton), taking into account country-specific recovered paper utilization rates.

Country	Pine from boreal biome	Pine from temperate biome	Broadleaf from temperate biome	Eucalyptus from subtropical biome	Eucalyptus from tropical biome
USA	1045	1940	1696	895	2439
Canada	1563	1571	1374		
China	1889	2124	1470	2344	2109
Finland	1864	1538	1420		
Sweden	1163	1072	1304		
Japan		1361	904	835	
Brazil				466	506
Russia	787	920	1119		
Indonesia					1195
India				965	1168
Chile		631	554	470	
France		718	942	389	
Germany		616	749		
Norway	1051	971	1181		
Portugal		1658	2017	848	
Spain		598	728	301	
South Africa				755	702
Austria		826	1004		
New Zealand		867	909	874	
Australia		993	823	623	657
Poland		1230	1048		
Thailand					759

Water footprint of paper products in industrial stage – example USA

In the USA, annual industrial production of paper products is around 97×10^6 ton/year. The total water use for the main water consumption categories is: E = 507×10^6 m^3, R = 19×10^6 m^3, P = 10×10^6 m^3 (Figure 2). A rough estimate then gives an average value of 5.5 m^3/ton for a paper product.

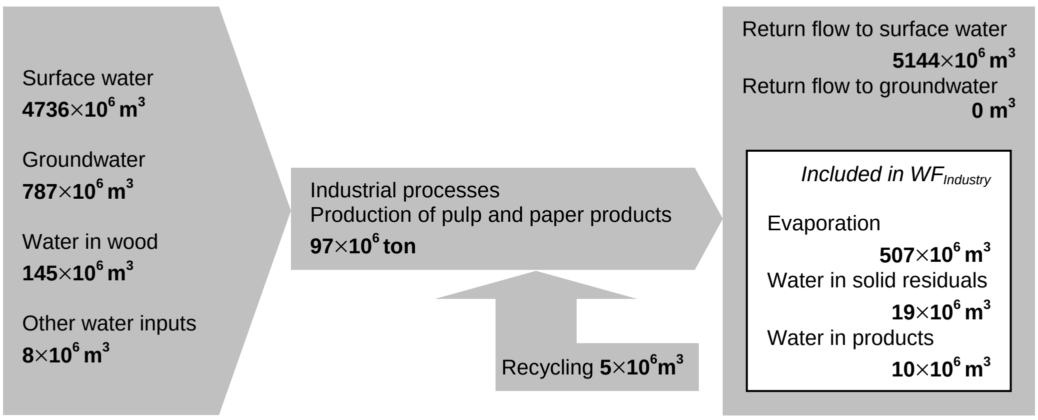

Figure 2. Water flows in the paper and pulp industry in the USA (NCASI, 2009).

3.2 The water footprint of paper consumption in the Netherlands

The Dutch water footprint related to the consumption of paper products is significant if compared to the footprint related to the consumption of other products. The water footprint of paper products is estimated to constitute 8-11% of the total water footprint of Dutch consumption (Van Oel et al., 2009). Figure 3 gives a summary of the water footprint accounts for the Netherlands insofar related to paper consumption, production and trade. Minimum and maximum estimates are given to account for the fact that paper products in the countries of origin can have a low or high water footprint depending on the biome from which the wood is derived (Tables 7-9).

Table 10 shows the water footprint of paper products in the Netherlands, whereby a distinction is made between: (i) paper produced from trees grown in the Netherlands, (ii) imported paper to the Netherlands or paper produced from imported pulp, and (iii) the weighed average. The water footprint of paper products produced from trees grown in the Netherlands is substantially lower (two to three times) than that of imported paper or paper produced from imported pulp. Most of the imported pulp originates from other European countries (85%), followed by North America (12%) (Figure 4).

If countries from which the Netherlands import pulp and paper would not recover paper as they currently do (Table 4) and if also the Netherlands itself would not recover paper, the water footprint of paper products consumed in the Netherlands would be 4.9-7.1 Gm^3/yr. Using recovered paper according to current rates has thus resulted in a water saving of 36%. For the Netherlands, the water footprint of a standard A4 copy paper (80 gram/m^2) is between 5 and 7 litres (7-10 litres if no recovered paper is used).

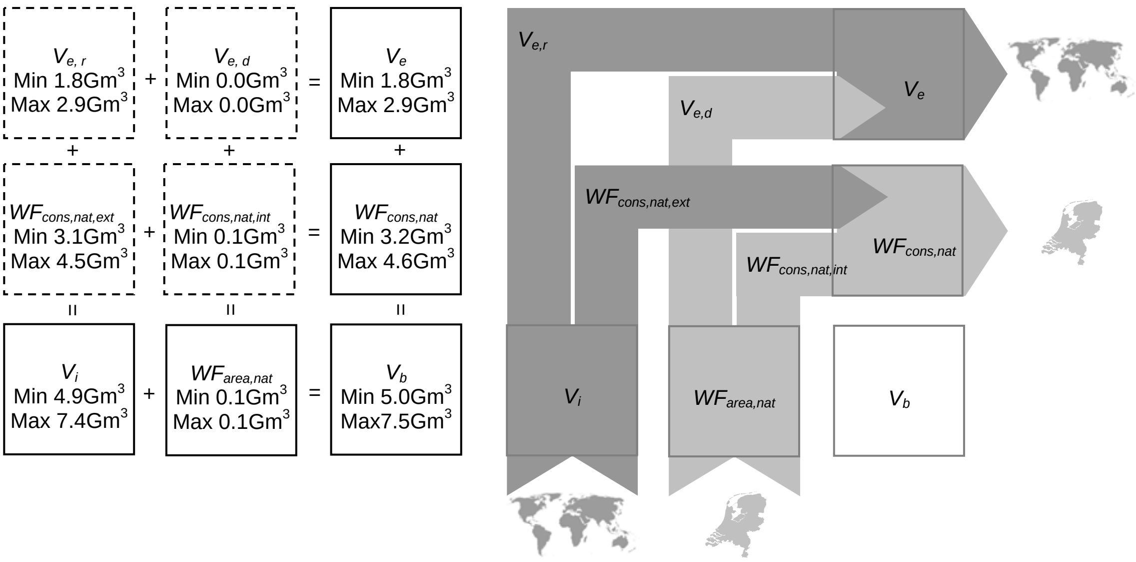

Figure 3. Summary of the water footprint accounts for the Netherlands insofar related to paper consumption, production and trade: virtual-water import (V_i), virtual-water export (V_e), the water footprint within the area of the nation ($WF_{area,nat}$) the water footprint related to national consumption ($WF_{cons,nat}$), the external water footprint ($WF_{cons,nat,ext}$), the internal water footprint ($WF_{cons,nat.int}$), the virtual-water re-export ($V_{e,r}$) and the virtual-water export from domestic production ($V_{e,d}$). The numbers in the boxes are minimum and maximum estimates for the period 1996–2005.

Table 10. Water footprint of paper products in the Netherlands.

Origin		Water footprint (m^3/ton)	
		Lower estimate	Higher estimate
Paper produced from trees grown in the Netherlands	Newsprint	369	410
	Printing & writing paper	451	501
	Other paper & paper board	423	470
Imported paper to the Netherlands or paper produced from imported pulp	Newsprint	829	1144
	Printing & writing paper	994	1402
	Other paper & paper board	848	1267
Average paper as on the Dutch market*	Newsprint	802	1101
	Printing & writing paper	962	1349
	Other paper & paper board	823	1221

* For the production of these products in the Netherlands it is assumed that pulp is used from imported and domestic sources in the same ratio as they are available (imported + produced). Around 94% of the available pulp in the Netherlands is imported.

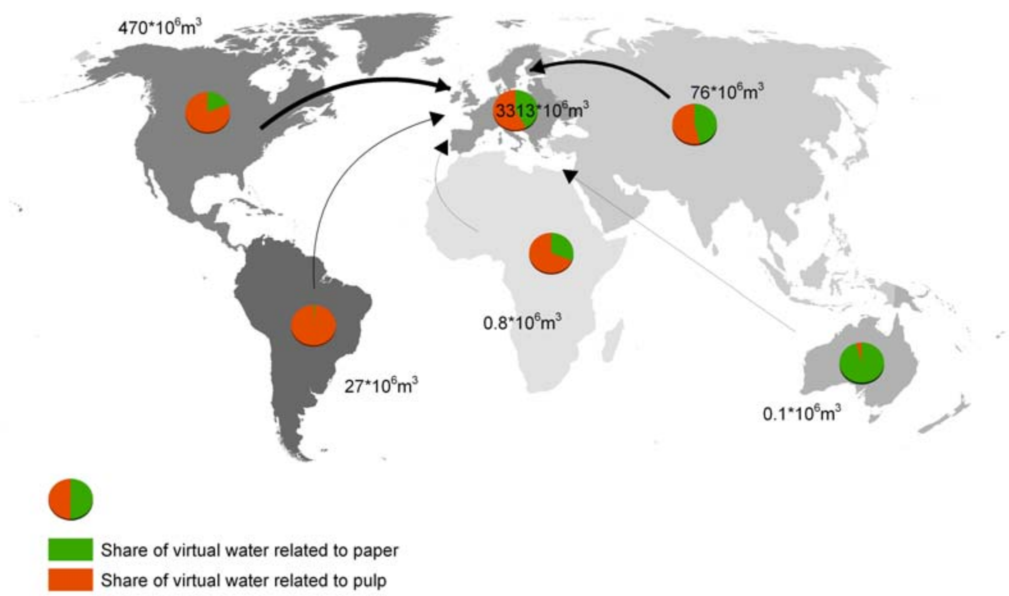

Figure 4. Virtual-water imports to the Netherlands by continent related to the import of pulp and paper.

4. Discussion

Allocation of forestry evapotranspiration to harvested wood. The water footprint is an indicator that takes into account the total use of freshwater for the production of a product. In the case of paper production from wood from a forest, it is not immediately clear what approach can best be chosen. Wood is harvested only after a number of years of growth. One could thus consider the evapotranspiration over the whole period from planting a forest until cutting it down and attribute that total evapotranspiration to the harvested wood. In practice, however, at a bit larger spatial scale, one can consider harvesting as an annual activity. Assuming a more or less stable demand for forestry products and a reasonable extent of sustainable forestry management practices, a rational approach is to relate the average annual evapotranspiration from the forest to the maximum sustainable annual yield. The maximum sustainable annual yield is the maximum annual yield that can be obtained for an infinite period of time. When actual yields from a forest are lower than the maximum sustainable annual yield (e.g. incidental wood harvesting in a non-production forest), it would be fair to attribute only a fraction of the annual evapotranspiration from the forest to the harvested wood, since the primary function of the forest is apparently other than for wood production. The fraction could be taken equal to Y_{act}/Y_{max}. In the case of a forest harvested according to the maximum sustainable annual yield (Y_{max}), we would take forest-ET over Y_{max}. In the case of a forest with an actual yield Y_{act}, we would take the fraction Y_{act}/Y_{max} times the forest-ET over Y_{act}, which results in the same water footprint estimate as in the case of the forest harvested at maximum sustainable annual yield. This illustrates the fact that the actual yield does not really influence the water footprint of the harvested wood. The two key factors are forest-ET and the rate of wood growth (Y_{max}).

Allocation of forestry evapotranspiration to harvested wood (2). There is another issue of allocation. Woodlands like semi-natural forests and plantations often serve purposes of considerable importance next to that of delivering wood for the production of paper. Next to the production of timber, important examples are biodiversity conservation and carbon storage. The appropriate way of accounting is to allocate the forest-ET over the various forest functions according to their economic value (Hoekstra et al., 2009). One would need estimates of the various values of forests, as for instance reported in Costanza et al. (1997). In this report we have not included the other values of a production forest. We have attributed the full forest-ET to the primary output of a production forest: wood.

Wood yields. Per biome we have estimated the maximum sustainable annual yield by assuming one typical tree type. In reality, many forest biomes are mixed with regard to tree types. For a boreal forest biome, pine trees have been assumed when taking data for the maximum sustainable annual yield, which is not precisely the case for all areas that are classified as boreal biome. For temperate, subtropical and tropical biomes, tree diversity may be even more diverse. Since actual evapotranspiration estimates are used for biomes rather than for specific tree types, this may cause inaccuracies.

Distinction between green and blue water. The green and blue water footprint requirements have been determined jointly. The difference between the use of green and the use of blue water is not as straightforward for forestry products as it is for other (agricultural) products. This difficulty is related to the process of water uptake by trees. The extent of the root zone of a full grown tree is generally well beyond the rainwater that is contained in the soil. Trees obtain water from the soil as well as from aquifers. More detailed studies are required to make a reliable estimate of the ratio green/blue in the water footprint of forestry products.

<u>Why measure green water footprint?</u> Traditional measurements of water use focus on blue water and exclude green water, so one may ask why include green water? Blue water scarcity is known because in several places on earth groundwater tables decline and rivers run dry. Both forestry and agriculture, however, strongly depend on green water. Also rainwater is scarce, although in a less obvious way. The water footprint indicator is designed to feed the debate on how limited freshwater resources are allocated over different purposes, similar to how the 'ecological footprint' is used to feed the debate on how we use the Earth's scarce productive lands (Rees, 1992; Hoekstra, 2009). The purpose of the green water footprint is to measure human's appropriation of the evaporative flow, just like the blue water footprint aims to measure human's appropriation of the runoff flow. The green water footprint measures the part of the evaporated rainwater that has been appropriated for certain human purposes and is therefore not available for other human purposes or nature. Green water used for production forest is not available for crop production or natural forest in the same place. The water footprint of a product thus shows the 'water allocated' to that product.

<u>Why measure consumptive water use instead of water withdrawal?</u> Industries are used to measure blue water withdrawals (Gleick, 1993; Van der Leeden, 1990), not consumptive blue water use as we do in the current study. Consumption refers to the part of the water withdrawal that really gets lost through evaporation, i.e. the part of the water withdrawal that does not return to the system from which it was withdrawn. If one is interested in the effect of water use at catchment scale, consumptive water use is a more meaningful indicator than water withdrawal, since generally the largest fraction of the water abstracted returns to the system and can be reused. The choice to look at consumptive water use explains why the 'blue water footprint' in the industrial stage of paper production found in this study is much lower than the figures on 'water use' generally reported by paper industries.

<u>Grey water</u>. The grey water footprint is not accounted for in this study. It is possible to produce paper without polluting water resources, which is achieved when effluents have a quality that is equal to or better than the intake water quality. Such a clean production process requires advanced purification techniques and is not yet applied in many production regions. Lack of worldwide data on both the quality of effluents and water bodies affected made it impossible to give reliable estimates for the grey water footprint of paper products.

<u>Variability in time</u>. In estimating the water footprints of paper products, we have not considered annual variations or changes over a longer period of time. For evapotranspiration, climate averages have been used (for the period 1961-1990). Including annual variations would raise practical difficulties, since it can take many years from the period of wood growth to the moment of consumption of the final paper product.

<u>Allocation in the case of recovered paper</u>. When recovered paper is used, a question is: how much of the water footprint in the forestry stage of the original wood should be allocated to the paper made in first instance, how

much to the paper made in the second round, how much to the paper in the third round, etc.? This issue becomes more complex due to the fact that paper products are often a mixture of wood pulp and pulp from recycled paper. The most simple solution is to fully allocate the water footprint in the forestry stage to the paper made in first instance. Then, pulp from recycled paper has no forestry-related water footprint. The water footprint of paper produced partly from wood pulp and partly from recycled paper-pulp can be calculated by weighing the water footprints of the two different sorts of pulp according to their relative input. An argument for such a simple calculation scheme is that beforehand it is not known how many times (if at all) a paper product will be recycled, so that there is little other choice than fully allocating the water footprint of wood pulp to the paper product that is directly made from it. If, however, one would be able to precisely trace recycling flows, one could also allocate the water footprint in the first stage of wood production to the final paper products produced in the different recycling stages, so that (decreasing) fractions of the forestry-related water footprint are allocated to the paper products in the subsequent recycling stages. The current study is a macro study, where we allocated the total annual water footprint in the forestry stage of paper production to the total annual paper production, whereby the latter is partly based on recycled paper. This method calculates an average water footprint of paper, which is good as an average and insensitive to the above-discussed allocation problem. If one would be interested, however, in the water footprint of a specific piece of paper, coming from a specific paper mill using a specific mixture of wood pulp and recycled paper-pulp, one would need to be explicit about the water footprint of the wood pulp versus the water footprint of the recycled paper-pulp. We would argue for taking the simple solution as proposed above.

<u>Scope of study</u>. Several processes that potentially contribute to the water footprint of paper products have been ignored. We have only included the water footprint of wood growth and paper processing; we have excluded the water footprint of other inputs (machineries, materials and energy) used in the process of making the final paper product and getting it to the consumer. One important process that may contribute substantially is related to transportation. For transportation a variety of alternative sources of energy may be used, including fossil fuels and bioenergy. Particularly when bioenergy is involved, the water footprint in transportation may be substantial (Gerbens-Leenes et al., 2009).

5. Conclusion

The water footprint of printing and writing paper is estimated to be between 300 and 2600 m^3/ton (2-13 litres for an A4 sheet). In these figures we have already accounted for the paper recovery rates as they currently are (Table 5). Without recovery, the global average water footprint of paper would be much larger; by using recovered paper an estimated 40% is saved globally. Further saving can be achieved by increasing the recovery percentages worldwide. For countries with a low recovered paper utilization rate a lot of room for reduction still remains. Some countries such as the Netherlands, Spain and Germany already use a lot of recovered paper. In addition, the global water footprint of paper can be reduced by choosing production sites and wood types that are more water-efficient.

For the Netherlands, the water footprint related to the consumption of paper products is significant. The water footprint of paper products is estimated to constitute 8-11% of the total water footprint of Dutch consumption.

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