WORKING PAPER IIT-16-107A

Parameterizing the water system for the SPATNEX-WE (Spatial and Temporal Nexus - Water Energy) model. Case study for Spain

August 27, 2016

Zarrar Khan

Zarrar.Khan@iit.comillas.es

Instituto de Investigación Tecnológica

Universidad Pontificia Comillas

Alberto Aguilera 23, 28015 Madrid, Spain

Abstract

With increasing pressures on both water and energy resources, integrated planning is an important strategy to optimize resource consumption. Several existing integrated water-energy models approach the nexus from the energy sector often underrepresenting the water system. A detailed model characterizing the water system has been developed by the authors in another paper and has been combined with an energy model to form a single integrated water-energy nexus model. To permit smooth integration of the two systems certain spatially and temporally disaggregated parameters need to be provided. This study presents the parameters needed to characterize the water system for integration. Starting from a conceptual hydrological cycle the different components of the water system are investigated: from the initial stages of precipitation; through natural processes such as evapotransipration, groundwater recharge and surface water interactions; through to human interception via reservoirs, rainwater harvesting, desalination, water purification, anthropological use and recycling; and finally to runoff. Water transfers between different river basins are also considered. Spain is used as a case study to demonstrate the process which can be repeated for other countries or regions. For each water system component the energy consumption, investment and operation costs, efficiency, existing resource availability and processing capacity as well as future impacts of climate change are developed. A worked example is also developed to demonstrate the use of the parameters for each component. The paper synthesizes the data into easily accessible summary tables and along with the water model paper, provides the tools necessary for future modelers to integrate the water system into existing energy systems in sufficient detail.

Contents

Chapter 1

Summary of Parameters

This section summarizes the different parameters of the water system. In order for integration with the energy system one of the main barriers has been the synchronization of water spatial and temporal data. To facilitate the integration process the data is aggregated by basin and by month, whihc is the time period chosen for the water data.

Table 1.1 shows the minumum, average and maximum values of the temperature, precipitation, groundwater levels, reservoir levels and demands from various sources which are discussed in detail in the Supplementary Information or working paper. The table can be used to intialize a water system model as well as to check model outputs and results to see if values are unusually high or low.

Table 1.2 shows the predicted changes for different water system processes. These values can be used to explore future scenarios and provide expected changes in the natural water cycle processes due to different climate change and socio-economic scenarios. IPCC scenarios descriptions, B2 medium changes, A2 high changes etc.

Table 1.3 summarizes the existing capacity of different water processes in Spain. This will allow model to predict how much additional capacity will be needed as a result of increased demand or decreased resources.

Finally Table 1.4 list the different parameters which characterise the different water processes. The parameters include estimated lifetimes, amortization rates, investment costs, operation costs, energy consumption and water losses. These parameters allow tracking costs, energy demands and losses for water flowing through each process. When linked with the energy model, the water system energy demands become an endogenous model input and at the same time the energy system water demands is fed into the water model as a variable input. The objective function can be formulated to include both water and energy outputs including costs, emission, losses etc.

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
GalCosta	Jan	5.8	8	10.6	456	2,594	5,429	226	259	307	19	46	75	30	295	534	x	x	x
	Feb	5	8.5	11.2	316	2,091	4,861	317	397	499	15	46	97	30	340	634	x	x	x
	Mar	8.1	10.2	13.4	182	1,876	5,177	486	605	783	23	37	59	30	391	634	x	x	x
	Apr	7.6	11.4	14.8	348	1,605	4,375	634	805	981	15	49	74	30	400	634	x	x	x
	May	10.5	13.6	16.4	172	1,491	3,261	806	990	1,116	6	29	49	30	392	634	x	x	x
	Jun	14.3	16.6	19.3	166	831	2,189	933	1,141	1,318	5	47	94	30	384	634	x	x	x
	Jul	16.2	18.5	20.6	89	502	1,511	749	1,044	1,273	6	47	92	30	341	634	x	x	x
	Aug	16.4	18.6	21.5	61	670	1,679	347	847	1,130	6	37	91	25	327	634	x	x	x
	Sep	14	17.1	19.5	162	1,172	2,946	215	739	885	18	27	56	15	327	634	x	x	x
	Oct	10.3	14.2	16.6	323	2,192	5,656	411	523	623	21	46	73	12	317	634	x	x	x
	Nov	8.5	10.6	13.6	234	2,478	5,001	268	313	385	7	35	69	9	318	634	x	x	x
	Dec	6.7	8.6	11.3	426	2,763	7,169	204	251	287	6	43	96	21	302	575	x	x	x
MinoSil	Jan	2.9	4.9	8.3	361	2,667	6,050	198	227	264	5	30	69	82	1,119	2,620	x	x	x
	Feb	1.5	5.9	9.3	406	2,329	7,039	297	392	492	9	41	64	82	1,249	2,611	x	x	x
	Mar	4.6	8	11.7	331	2,033	5,618	537	677	886	11	63	202	100	1,366	2,708	x	x	x
	Apr	5.5	9.6	14.1	483	1,712	4,623	740	963	1,189	6	19	55	126	1,436	2,653	x	x	x

continue

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	May	8	12.3	16.2	266	1,670	3,486	973	1,182	1,373	22	65	96	109	1,492	2,638	x	x	x
	Jun	13.2	16.1	20.6	272	1,024	2,360	1,083	1,328	1,582	6	52	206	97	1,492	2,708	x	x	x
	Jul	15.7	18.6	21	27	542	2,110	866	1,125	1,643	7	53	100	82	1,394	2,524	x	x	x
	Aug	15.8	18.4	21.5	65	627	1,670	377	858	1,264	14	50	102	82	1,269	2,266	x	x	x
	Sep	12.9	16.2	19.6	149	1,220	3,359	348	803	1,108	11	34	74	110	1,162	2,113	x	x	x
	Oct	8	12.3	14.8	208	2,298	6,074	333	574	718	7	42	61	187	1,054	2,087	x	x	x
	Nov	5.2	7.9	10.5	123	2,550	6,011	238	289	348	11	47	93	167	1,044	2,330	x	x	x
	Dec	2.4	5.4	8.5	294	3,030	9,162	175	205	228	23	78	184	131	1,048	2,566	x	x	x
CantbrOc	Jan	1.3	5.1	8.3	288	2,375	4,950	276	323	373	19	50	96	187	328	437	x	x	x
	Feb	0	5.8	10.1	325	1,974	3,752	367	494	610	5	40	73	150	359	511	x	x	x
	Mar	3.9	7.7	11.3	319	1,871	3,610	655	776	884	5	39	89	226	390	512	x	x	x
	Apr	5.8	9	11.9	287	1,996	4,684	795	1,023	1,162	18	61	100	273	401	511	x	x	x
	May	8.4	11.6	14.5	517	1,887	4,221	888	1,195	1,356	5	33	91	215	397	511	x	x	x
	Jun	12.6	14.8	17.6	334	1,171	4,005	795	1,146	1,481	14	53	96	235	394	511	x	x	x
	Jul	14.8	17	19.6	275	821	2,898	568	941	1,448	14	46	96	179	365	511	x	x	x

continued

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Aug	14.7	17.1	20.6	243	973	2,862	361	855	1,344	18	31	51	177	357	511	x	x	x
	Sep	11.7	15.4	18.5	151	1,349	3,852	261	850	1,124	20	59	194	174	352	511	x	x	x
	Oct	8.1	12.1	15.3	380	2,170	5,593	365	675	803	25	50	97	174	340	511	x	x	x
	Nov	5.2	8	11.3	297	2,591	5,410	310	401	480	17	66	197	150	330	511	x	x	x
	Dec	2.6	5.8	9.8	236	2,661	6,036	261	303	362	17	49	77	111	320	458	x	x	x
CantbrOr	Jan	1.9	5.7	9.8	107	858	1,899	106	130	157	15	45	78	0	32	81	x	x	x
	Feb	-0.7	6.4	11.3	196	700	1,398	129	180	230	6	33	60	2	35	89	x	x	x
	Mar	3.8	8.4	11.8	161	687	1,740	218	269	322	14	49	104	3	40	89	x	x	x
	Apr	6.9	9.9	13.4	196	829	1,638	278	348	428	5	44	83	14	41	89	x	x	x
	May	9.6	12.9	15.9	203	652	1,230	344	427	496	14	46	96	0	40	90	x	x	x
	Jun	13	15.7	19.7	135	445	1,133	326	434	531	5	39	77	11	38	89	x	x	x
	Jul	14.5	17.8	21.2	79	335	866	213	376	488	6	34	72	9	33	89	x	x	x
	Aug	15.3	18	22.7	154	425	1,263	205	352	477	12	23	48	6	33	89	x	x	x
	Sep	12.7	16.3	19.8	99	547	1,056	148	332	425	21	44	75	4	35	89	x	x	x
	Oct	8.6	13.2	17.1	97	754	2,522	178	246	298	16	50	71	4	34	89	x	x	x

continue

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Nov	5.8	8.8	12.3	169	933	1,922	123	154	196	5	34	79	3	36	90	x	x	x
	Dec	3.3	6.4	11.5	169	954	2,461	96	120	143	6	36	60	2	34	81	x	x	x
Duero	Jan	-0.1	2.8	5.5	498	5,096	14,776	965	1,156	1,371	5	23	56	1,035	3,389	6,638	x	x	x
	Feb	-0.9	4.1	7.6	803	4,307	12,999	1,639	2,115	2,647	11	44	75	1,342	3,711	6,584	x	x	x
	Mar	3.1	6.8	10.2	419	4,037	11,212	2,374	3,572	4,793	5	39	79	1,481	4,311	6,918	x	x	x
	Apr	5.1	8.8	13	721	4,454	9,946	3,302	4,882	6,126	7	54	97	1,863	4,501	7,053	x	x	x
	May	7.8	12.4	16.4	1,579	4,945	10,404	3,605	5,927	7,774	13	33	76	1,905	4,447	6,874	x	x	x
	Jun	13.4	16.8	20.2	730	3,305	8,800	2,034	5,490	7,820	12	46	100	1,838	4,185	6,738	x	x	x
	Jul	16.5	19.9	22.5	190	1,665	5,364	599	2,981	6,989	6	36	97	1,695	3,744	5,882	x	x	x
	Aug	17	19.5	22.6	132	1,579	4,833	445	1,877	4,499	18	45	83	1,358	3,539	5,458	x	x	x
	Sep	13.1	16.3	19.5	444	3,115	7,593	595	2,756	5,528	21	57	101	968	3,606	6,851	x	x	x
	Oct	7.4	11.4	14.4	536	5,039	15,785	548	2,628	3,497	8	35	109	809	3,574	7,053	x	x	x
	Nov	3.7	6.4	9.4	368	5,385	13,868	640	1,574	1,949	18	66	103	658	3,480	6,618	x	x	x
	Dec	0.2	3.4	7.3	755	5,462	14,200	846	1,065	1,269	17	57	95	776	3,404	6,078	x	x	x
Ebro	Jan	0.6	3.8	6.8	436	4,433	12,276	964	1,374	1,634	19	56	93	555	2,603	4,863	x	x	x

continued

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Feb	-0.9	5.2	9.4	985	3,742	8,783	1,481	2,277	3,077	5	42	77	574	2,752	5,766	x	x	x
	Mar	4.2	8	11.2	572	4,110	10,654	2,341	3,575	4,870	6	47	95	617	3,304	6,430	x	x	x
	Apr	7.2	10.3	13.8	1,571	5,444	12,844	3,009	4,671	5,980	18	43	93	652	3,338	6,082	x	x	x
	May	9.8	14	17	2,143	6,182	15,141	3,253	5,677	7,304	11	46	94	683	3,319	5,782	x	x	x
	Jun	14.8	18.2	22.4	1,366	4,577	11,305	2,872	5,428	7,681	5	44	90	693	3,231	5,766	x	x	x
	Jul	18.4	21.2	24.1	719	2,753	7,014	1,521	3,644	6,151	17	45	102	630	2,870	5,766	x	x	x
	Aug	18.4	20.9	24.2	988	3,440	8,839	1,487	3,296	6,225	28	45	67	525	2,711	5,766	x	x	x
	Sep	13.6	17.6	21	913	4,780	11,840	1,274	3,681	5,884	24	51	65	328	2,946	6,456	x	x	x
	Oct	8.6	12.8	15.8	1,418	5,384	14,942	1,328	2,808	3,748	24	52	96	346	2,861	6,108	x	x	x
	Nov	5	7.5	10.3	744	5,238	15,213	757	1,735	2,061	6	41	79	390	2,842	5,808	x	x	x
	Dec	1.8	4.4	7.8	973	5,132	11,216	894	1,219	1,412	9	35	68	495	2,711	5,186	x	x	x
CICat	Jan	2.3	5.8	8.8	46	744	3,194	239	294	357	5	40	81	14	318	618	x	x	x
	Feb	1.2	7	10.8	77	675	2,706	328	472	551	5	48	205	14	325	582	x	x	x
	Mar	5.2	9.5	12.5	139	844	2,409	532	727	852	6	49	99	22	360	659	x	x	x
	Apr	9.1	11.8	14.5	214	1,038	3,496	520	995	1,191	11	24	71	29	357	650	x	x	x

continued

...continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	May	12.3	15.4	18.1	222	1,260	3,219	758	1,188	1,437	5	51	187	27	351	597	x	x	x
	Jun	16	19.4	23	137	989	2,888	458	1,156	1,627	5	32	98	26	363	623	x	x	x
	Jul	19.8	22.4	25.2	132	640	1,603	277	846	1,529	18	84	325	28	357	618	x	x	x
	Aug	18.7	22.2	25.3	283	1,034	2,346	459	934	1,513	19	51	66	23	351	582	x	x	x
	Sep	12.8	19.1	22.4	329	1,281	3,318	360	910	1,217	17	80	385	17	366	659	x	x	x
	Oct	10.2	14.7	17.3	219	1,327	4,315	234	619	785	6	54	97	1	350	650	x	x	x
	Nov	7.1	9.5	12.2	97	933	2,862	138	357	422	9	61	196	1	330	597	x	x	x
	Dec	3.9	6.5	9.4	112	1,000	3,032	174	269	308	5	33	77	1	326	542	x	x	x
Tajo	Jan	-0.1	4.7	7.5	335	3,883	13,716	816	1,072	1,332	6	39	103	1,163	4,982	8,257	x	x	x
	Feb	0.9	6.1	9.8	340	3,590	10,870	1,508	1,836	2,233	9	56	97	1,283	5,380	8,807	x	x	x
	Mar	5.9	8.9	12.7	371	3,203	8,964	2,052	2,945	3,803	10	52	98	1,272	5,958	9,262	x	x	x
	Apr	7.9	11.3	14.5	441	3,424	7,703	2,128	3,932	4,967	22	42	78	1,567	6,167	9,241	x	x	x
	May	10.1	15	19.5	733	3,371	7,933	1,678	4,183	5,441	13	36	101	1,715	6,126	9,345	x	x	x
	Jun	16.5	20	23.3	476	1,978	6,976	1,067	3,155	5,517	15	55	98	1,879	5,900	8,628	x	x	x
	Jul	20.6	23.6	26.1	49	732	2,936	253	1,378	3,427	17	38	58	1,866	5,596	8,191	x	x	x

continued

. . . continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Aug	19.9	23.2	25.9	103	755	2,469	195	902	2,405	22	48	79	1,727	5,445	8,191	x	x	x
	Sep	13.3	19.4	23.2	259	2,168	6,634	332	1,915	4,224	24	45	93	1,583	5,483	8,430	x	x	x
	Oct	10.1	13.9	17.7	286	3,927	11,942	291	2,142	3,083	6	35	98	1,051	5,398	8,599	x	x	x
	Nov	5.7	8.5	11.3	386	4,120	12,298	390	1,420	1,724	18	54	100	920	5,264	8,362	x	x	x
	Dec	2.4	5.3	8.9	641	4,321	13,117	870	972	1,106	6	42	93	808	5,072	8,517	x	x	x
Guadiana	Jan	2.6	6.5	9.2	218	3,304	11,691	963	1,120	1,350	16	45	94	736	3,186	7,446	x	x	x
	Feb	3.3	7.9	11	330	3,181	10,634	1,283	1,869	2,297	10	50	86	803	3,479	8,419	x	x	x
	Mar	7.3	10.7	14.2	305	2,802	7,640	1,867	2,991	4,072	5	34	77	857	3,898	8,419	x	x	x
	Apr	9.2	13	16.6	460	3,027	7,378	1,225	3,980	5,095	18	35	76	839	4,096	8,419	x	x	x
	May	12.1	16.8	21.2	480	2,545	6,477	886	4,164	5,841	15	61	190	815	4,061	8,419	x	x	x
	Jun	17.4	21.9	25	321	1,483	5,123	620	2,730	5,398	6	36	64	777	3,874	8,419	x	x	x
	Jul	22.1	25.6	28.1	13	358	2,160	65	617	2,377	22	50	68	737	3,719	8,419	x	x	x
	Aug	21.7	25.2	27.7	47	484	2,118	51	494	2,100	16	56	204	698	3,686	8,419	x	x	x
	Sep	16.4	21.5	24.5	77	1,589	4,237	78	1,536	3,743	6	62	109	673	3,831	8,419	x	x	x
	Oct	12.5	16	19.1	180	3,212	9,111	181	2,123	3,234	20	52	102	362	3,867	8,419	x	x	x

continued

...continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Nov	7.2	10.5	13.5	224	3,306	9,043	224	1,423	1,757	11	46	79	332	3,835	8,419	x	x	x
	Dec	4.1	7.2	10.5	343	3,793	12,566	847	994	1,122	6	39	101	322	3,476	7,588	x	x	x
Jucar	Jan	2.5	6.2	9	119	1,724	4,889	429	871	1,064	10	40	79	296	1,126	2,360	x	x	x
	Feb	1.6	7.3	11.1	141	1,749	4,474	862	1,368	1,824	5	29	60	316	1,268	2,778	x	x	x
	Mar	5.7	9.7	13	236	1,766	4,364	1,045	1,972	2,580	15	46	93	388	1,455	2,778	x	x	x
	Apr	9.6	11.9	15.3	707	2,182	6,186	1,033	2,456	3,254	5	25	65	436	1,487	2,778	x	x	x
	May	11.7	15.5	18.8	378	2,366	5,495	707	2,735	3,834	5	40	89	393	1,432	2,778	x	x	x
	Jun	16.3	19.9	23.1	280	1,642	5,255	492	2,311	4,166	17	57	102	349	1,355	2,778	x	x	x
	Jul	20.5	23.4	25.6	92	683	2,333	258	1,078	2,405	15	40	64	253	1,227	2,778	x	x	x
	Aug	20.1	23.3	25.4	177	1,059	2,815	245	1,093	2,540	16	45	80	205	1,231	2,778	x	x	x
	Sep	15.1	19.8	22.6	311	2,070	5,643	389	1,728	3,224	6	48	98	165	1,317	2,778	x	x	x
	Oct	11.5	14.9	18.2	461	2,702	7,484	465	1,555	2,161	21	53	86	131	1,312	2,778	x	x	x
	Nov	7.4	10	12.6	174	2,016	5,632	177	995	1,253	6	20	56	200	1,282	2,778	x	x	x
	Dec	4.4	6.9	9.4	271	2,199	5,718	317	790	930	10	43	94	261	1,194	2,480	x	x	x
TintOdPdra	Jan	7.6	10.1	12.9	29	431	1,608	104	132	154	5	34	88	16	93	180	x	x	x

continued

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Feb	6.3	11.2	14.5	22	362	1,296	155	196	236	15	52	98	15	98	210	x	x	x
	Mar	10.9	13.4	16.8	29	317	763	194	303	373	6	28	65	17	110	212	x	x	x
	Apr	11.6	15.4	20.8	10	281	833	120	389	489	25	48	99	19	116	223	x	x	x
	May	14.9	18.5	22.8	9	182	581	79	405	568	19	57	97	16	116	225	x	x	x
	Jun	19.1	22.7	25.6	6	72	384	17	216	477	14	46	68	14	113	225	x	x	x
	Jul	23.4	26	28.1	1	13	78	1	30	153	16	44	83	14	102	210	x	x	x
	Aug	23.7	26	28.2	1	23	179	1	23	178	15	47	101	12	106	210	x	x	x
	Sep	18.5	23.2	26.3	7	127	575	7	121	462	38	71	99	12	116	212	x	x	x
	Oct	15.5	18.7	21.6	13	359	1,309	13	216	350	6	25	66	11	123	223	x	x	x
	Nov	11.3	14.1	17.6	24	401	1,207	24	164	211	11	51	102	14	124	225	x	x	x
	Dec	8.8	10.9	13.5	31	478	1,601	91	122	141	10	49	95	14	111	195	x	x	x
Guadalquivir	Jan	4.2	7.6	10.2	213	4,155	14,321	1,065	1,378	1,626	17	73	184	585	2,782	6,292	x	x	x
	Feb	4.6	9	12	353	3,878	12,469	1,301	2,163	2,676	5	42	86	672	3,054	7,877	x	x	x
	Mar	8.6	11.6	14.8	376	3,529	9,110	2,165	3,298	4,133	16	37	77	788	3,467	7,877	x	x	x
	Apr	10	13.8	17.5	223	3,380	8,874	1,209	4,201	5,211	8	54	183	865	3,660	7,877	x	x	x

continued

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	May	12.9	17.4	22	320	2,565	7,163	550	4,279	5,972	5	38	75	855	3,620	7,877	x	x	x
	Jun	17.8	22.1	24.9	183	1,148	4,954	286	2,398	5,779	17	47	63	793	3,406	7,922	x	x	x
	Jul	22.6	25.8	27.8	25	242	1,968	47	457	1,853	19	52	215	585	3,129	7,922	x	x	x
	Aug	22.3	25.6	27.4	28	388	2,040	34	405	1,987	6	56	99	646	3,042	7,928	x	x	x
	Sep	17.1	22	25	82	1,587	5,421	85	1,506	4,571	6	21	48	566	3,223	7,928	x	x	x
	Oct	13.6	16.8	19.4	204	3,559	12,523	205	2,262	3,565	21	74	194	197	3,302	7,928	x	x	x
	Nov	8.3	11.6	14.4	203	4,094	11,836	203	1,669	2,020	7	35	57	193	3,348	7,928	x	x	x
	Dec	6.1	8.4	11.1	536	4,861	17,483	609	1,305	1,463	12	40	65	821	3,072	7,036	x	x	x
Segura	Jan	4	7.9	11	45	595	1,487	119	385	531	6	31	65	85	472	1,612	x	x	x
	Feb	3.8	9.1	12.4	33	609	1,761	251	565	799	23	40	97	109	516	1,724	x	x	x
	Mar	7.2	11.5	15	110	653	2,154	196	698	1,167	5	30	54	130	615	1,992	x	x	x
	Apr	10.9	13.7	17.1	163	826	3,511	229	855	1,469	18	50	68	102	642	2,000	x	x	x
	May	14.1	17.3	21.2	71	742	2,416	119	843	1,648	5	45	98	69	606	1,846	x	x	x
	Jun	18.2	21.6	24.4	53	457	1,874	72	579	1,598	16	29	46	65	552	1,714	x	x	x
	Jul	22.4	25	27.4	11	131	779	19	176	785	16	54	84	39	505	1,634	x	x	x

continued

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Aug	21.8	25	27	21	243	1,226	22	243	1,181	6	51	105	36	500	1,724	x	x	x
	Sep	16.1	21.4	24	61	621	2,436	61	565	1,582	11	65	102	33	553	1,992	x	x	x
	Oct	11.9	16.6	19	81	911	2,798	81	627	1,060	18	40	74	22	578	2,000	x	x	x
	Nov	9.1	11.8	14.3	37	710	1,955	37	443	616	11	42	94	35	569	1,846	x	x	x
	Dec	5.3	8.6	11.1	42	738	2,817	116	349	445	18	39	56	88	518	1,623	x	x	x
GuadBarbte	Jan	6.8	10.7	13.5	16	665	2,604	100	261	308	17	50	103	34	491	1,353	x	x	x
	Feb	7.6	11.7	14.3	33	584	2,192	154	338	395	16	42	76	42	543	1,591	x	x	x
	Mar	11.3	13.7	16.4	34	489	1,589	218	447	558	11	49	101	62	610	1,591	x	x	x
	Apr	11.8	15.4	18.5	25	374	1,178	170	501	648	5	61	196	76	646	1,591	x	x	x
	May	14.7	18.3	21.2	14	261	918	27	420	715	5	44	101	66	642	1,591	x	x	x
	Jun	18.3	21.9	24.8	3	82	456	6	159	580	16	39	77	57	599	1,591	x	x	x
	Jul	21.6	25.1	27.2	1	8	63	1	17	85	5	56	192	34	568	1,591	x	x	x
	Aug	22.8	25.4	28.7	1	28	343	1	29	328	6	57	99	31	573	1,591	x	x	x
	Sep	19.6	22.8	25.6	6	163	749	6	156	625	39	56	83	22	606	1,591	x	x	x
	Oct	15.8	18.9	21.4	23	484	1,718	23	314	560	12	38	99	10	629	1,591	x	x	x

continued

…continued

Table 1.1: Historical data for water system processes

Basin	Month	Temperature °C 1941-2010			Precipitation hm^3 1941-2010			ETR hm^3 1941-2010			GW Levels m 2003-2012			Reservoir Volume hm^3 1958-2012			Demand hm^3 Est. 2012		
		min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	nrg	ind	agr
	Nov	11.2	14.5	17.3	28	663	2,772	28	301	382	24	43	58	10	639	1,591	x	x	x
	Dec	9.4	11.5	14.2	44	813	2,874	48	248	315	12	43	73	45	567	1,472	x	x	x
CMedAndlz	Jan	6.2	9.3	12.1	64	1,261	4,940	233	528	666	23	48	90	117	446	793	x	x	x
	Feb	5.8	10.2	12.8	78	1,161	3,853	350	697	834	5	41	94	147	517	965	x	x	x
	Mar	8.8	12.1	14.7	127	1,052	2,928	416	892	1,124	15	41	64	178	618	965	x	x	x
	Apr	10.8	14	17.7	138	925	2,561	230	997	1,447	23	46	94	210	652	965	x	x	x
	May	13.2	17	20.2	57	612	1,806	73	863	1,485	15	49	97	230	634	965	x	x	x
	Jun	17.8	21	24.2	21	231	1,516	29	406	1,320	6	44	83	175	589	965	x	x	x
	Jul	21.3	24.3	26.7	3	45	308	4	70	305	25	59	97	117	558	965	x	x	x
	Aug	21.4	24.6	26.8	9	111	848	11	107	758	11	47	96	147	607	965	x	x	x
	Sep	16.8	21.5	24.1	39	459	1,803	39	413	1,394	13	22	34	178	680	965	x	x	x
	Oct	13.7	17.1	19.4	69	1,034	2,789	70	662	1,089	10	41	66	319	726	965	x	x	x
	Nov	10.2	12.9	15.5	71	1,306	4,685	69	592	764	14	47	71	299	707	965	x	x	x
	Dec	7.4	10	12.1	54	1,525	5,441	59	482	581	5	30	66	342	574	879	x	x	x

Table 1.2: Predicted water system process changes due to climate change

Basin	Peroid	Temperature						Precipitation						ETR					
		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100	
		A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
Spain	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
GalCosta	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
MinoSil	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
CantbrOc	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

continued ...

…continued

Table 1.2: Predicted water system process changes due to climate change

Basin	Peroid	Temperature						Precipitation						ETR					
		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100	
		A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
CantbrOr	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Duero	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Ebro	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

continued…

...continued

Table 1.2: Predicted water system process changes due to climate change

Basin	Peroid	Temperature						Precipitation						ETR					
		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100	
		A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
CICat	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Tajo	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Guadiana	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

continued ...

…continued

Table 1.2: Predicted water system process changes due to climate change

Basin	Peroid	Temperature						Precipitation						ETR					
		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100	
		A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Jucar	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
TintOdPdra	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Guadalquivir	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

continued…

…continued

Table 1.2: Predicted water system process changes due to climate change

Basin	Peroid	Temperature						Precipitation						ETR					
		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100		2011-2040		2041-2070		2071-2100	
		A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Segura	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
GuadBarbte	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
CMedAndlz	Annual	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Oct,Nov,Dec	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jan,Feb,Mar	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Apr,May,Jun	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Jul,Aug,Sep	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Table 1.3: Existing capacity of technologies per basin $hm^3/month$

Basin	Desal	Transfers	Dist	GWPump	Purif	Recycling	RWHarvest	Reservoirs
GalCosta	x	x	x	x	x	x	x	x
MinoSil	x	x	x	x	x	x	x	x
CantbrOc	x	x	x	x	x	x	x	x
CantbrOr	x	x	x	x	x	x	x	x
Duero	x	x	x	x	x	x	x	x
Ebro	x	x	x	x	x	x	x	x
CICat	x	x	x	x	x	x	x	x
Tajo	x	x	x	x	x	x	x	x
Guadiana	x	x	x	x	x	x	x	x
Jucar	x	x	x	x	x	x	x	x
TintOdPdra	x	x	x	x	x	x	x	x
Guadalquivir	x	x	x	x	x	x	x	x
Segura	x	x	x	x	x	x	x	x
GuadBarbte	x	x	x	x	x	x	x	x
CMedAndlz	x	x	x	x	x	x	x	x

continued . . .

…continued

Table 1.4: Water system process parameters

Table 1.4: Water system process parameters

| Parameter | Units | Desal | Transfers | Dist | GWPump | Purif | Recycling | RWHarvest | Reservoirs |

Parameter	Units	Desal	Transfers	Dist	GWPump	Purif	Recycling	RWHarvest	Reservoirs
Lifetime	yrs	x	x	x	x	x	x	x	x
Amort. rate	%	x	x	x	x	x	x	x	x
Invs. Cost	$€/m^3$	x	x	x	x	x	x	x	x
Op. Cost	$€/m^3$	x	x	x	x	x	x	x	x
Energy	kWh/m^3	x	x	x	x	x	x	x	x
Losses	%	x	x	x	x	x	x	x	x

1.1 Worked Example

An minimum working example is developed below to demonstrate how the different parameters may be used.

Assume:

- Basin X has a capacity of 1000 L/s installed
- Water needed is in the month is 6,000,000,000 L
- Groundwater depth is 50m
- Liftime is 30 years, interest rate is 4%

Using the values from the parameter table we can calculate costs, energy and losses as follows:

- Water provided by current capacity = 1000 $L/s \times 60 \times 60 \times 24 \times 30 = 3,000,000,000$ $L/month = 3\ hm^3/month$
- Additional capacity needed is = $6,000,000,000 - 3,000,000,000\ L/month = 3,000,000,000$ $L/month = 1000\ L/s = 2.6\ hm^3/month$
- Investment cost (€) = $5529e/(hm^3/month)/m \times 2.6hm^3/month \times 50(m) = 716,548$ €
- Annuity (€) = $P(i + i/((1+i)^n - 1)) = 716,548 \times (0.04 + 0.04/(1.04)^{30} - 1) = 41,438$ €
- OnM costs (€) = 3,913 €$/(hm3) \times 6(hm^3)$ = 23,478 €
- Power needed $(kW) = 2315(L/s) \times 50(m)/(102 \times 0.8 \times 0.8) = 1891(kW)$
- Energy needed (GWh):
  - Using Equation 5.5.1 [1]
    $= 1891 \times 30(days) \times 24(hrs)/10E6 = 1.36GWh$
  - Using Equation 5.5.2 [2]
    = 6 (hm^3) × 50 (m) × 0.5 × 9.8 (m/s^2) × 1000 (kg/m^3) / (1000 × 1000) = 1.47 GWh
- Water losses are taken to be 0 for groundwater pumping since any loses in piping are assumed to go back to the aquifer.

Chapter 2

Precipitation and evapotranspiration

2.1 Key Points

2.2 Introduction

2.3 Parameter Summary

2.4 Existing Resources

Temperature

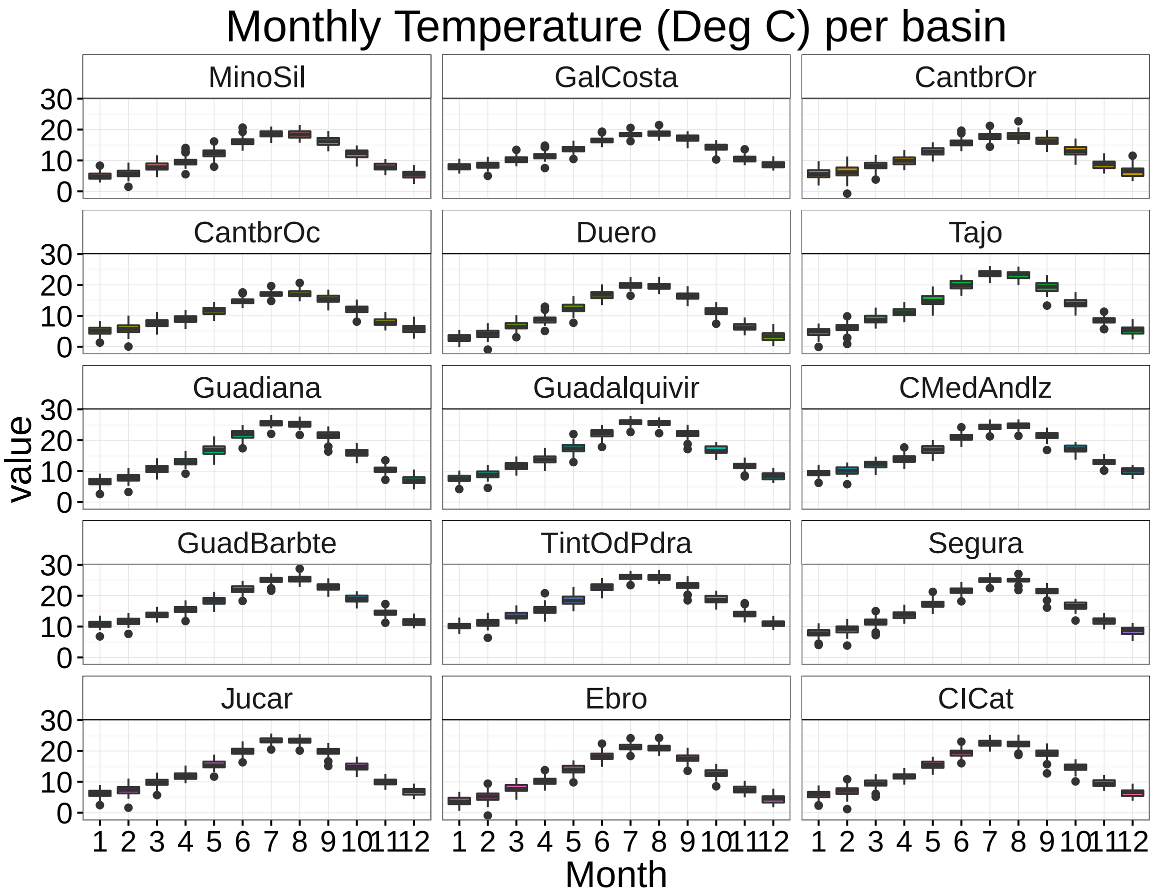

Figure 2.1: Temperature in Degrees Celcius boxplot 1941-2010

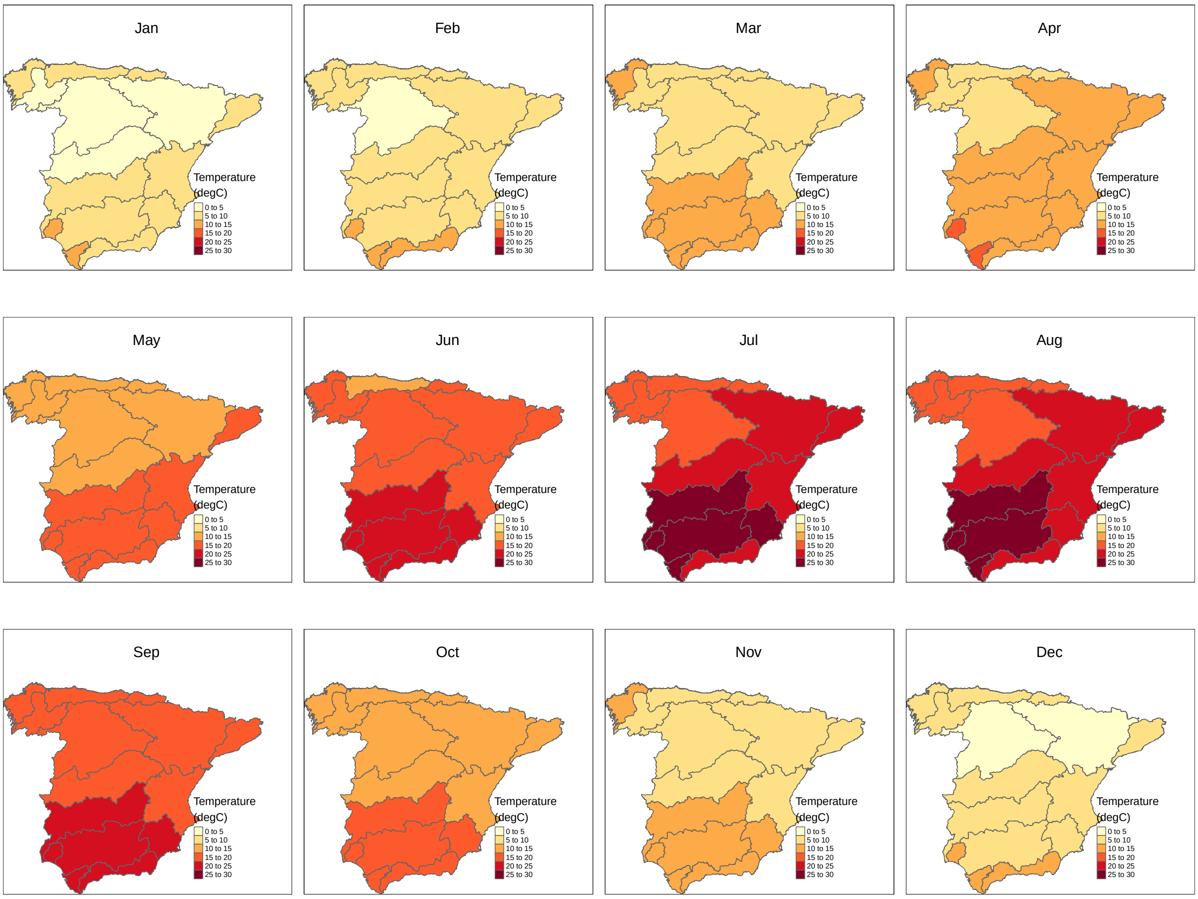

Figure 2.2: Temperature in Degrees Celcius monthly 1941-2010

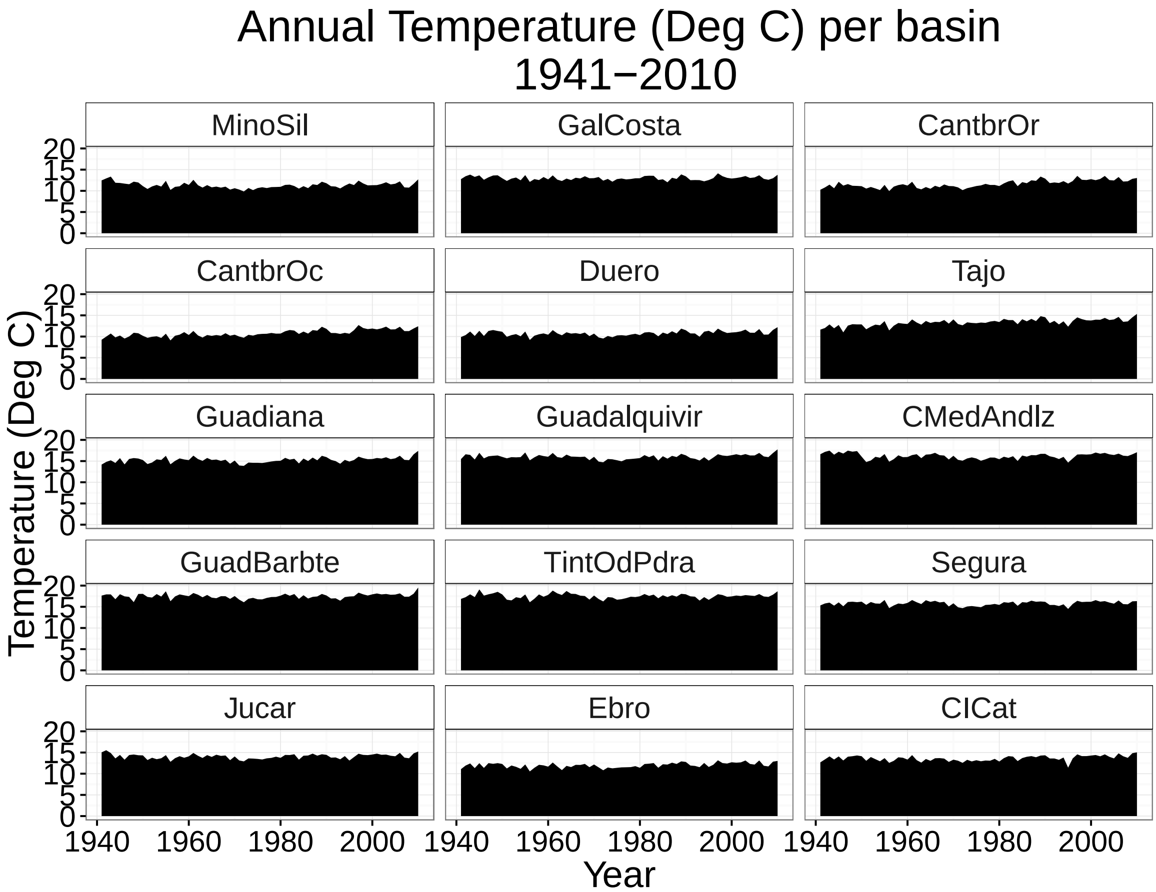

Figure 2.3: Temperature in Degrees Celcius Annual barplot 1941-2010

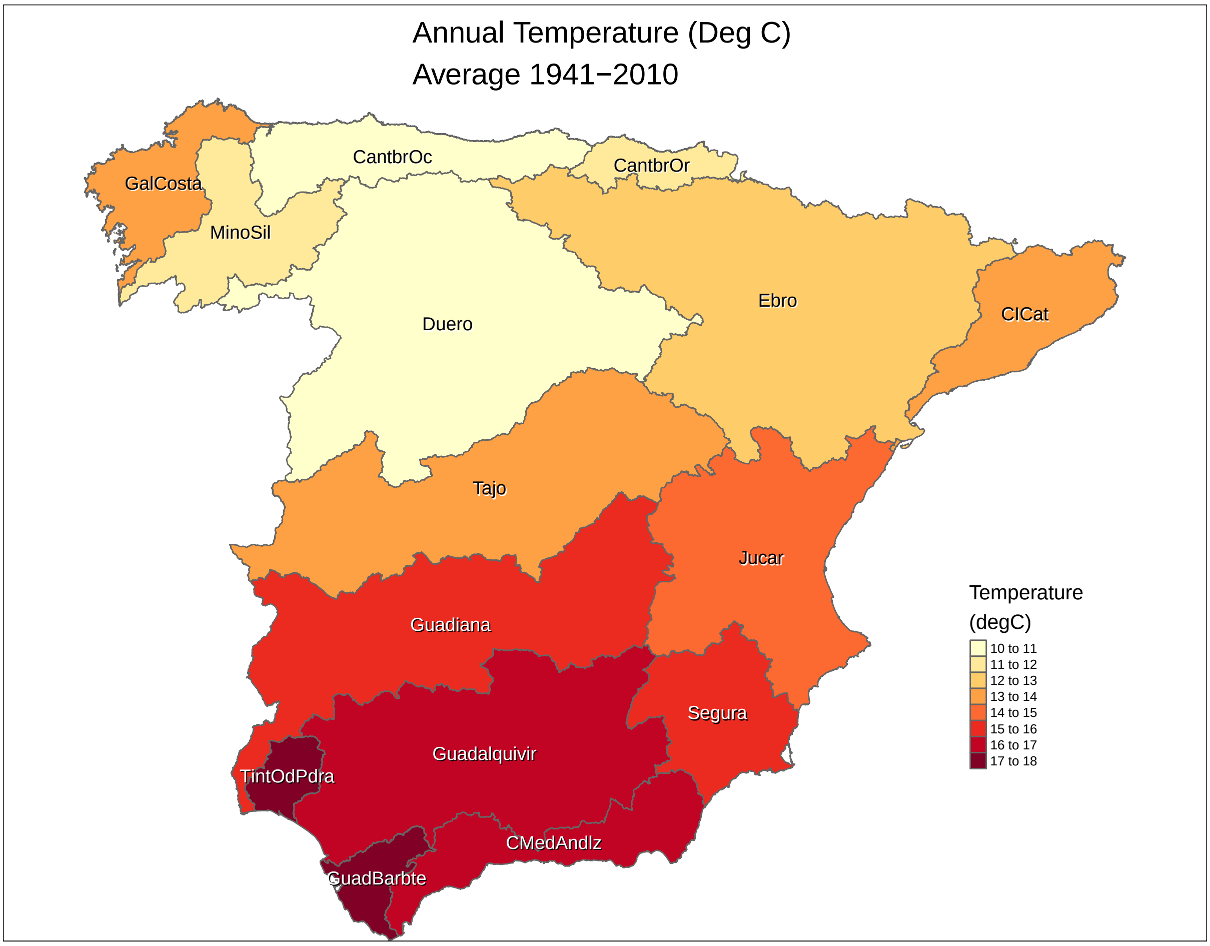

Figure 2.4: Temperature in Degrees Celcius Annual map 1941-2010

Precipitation

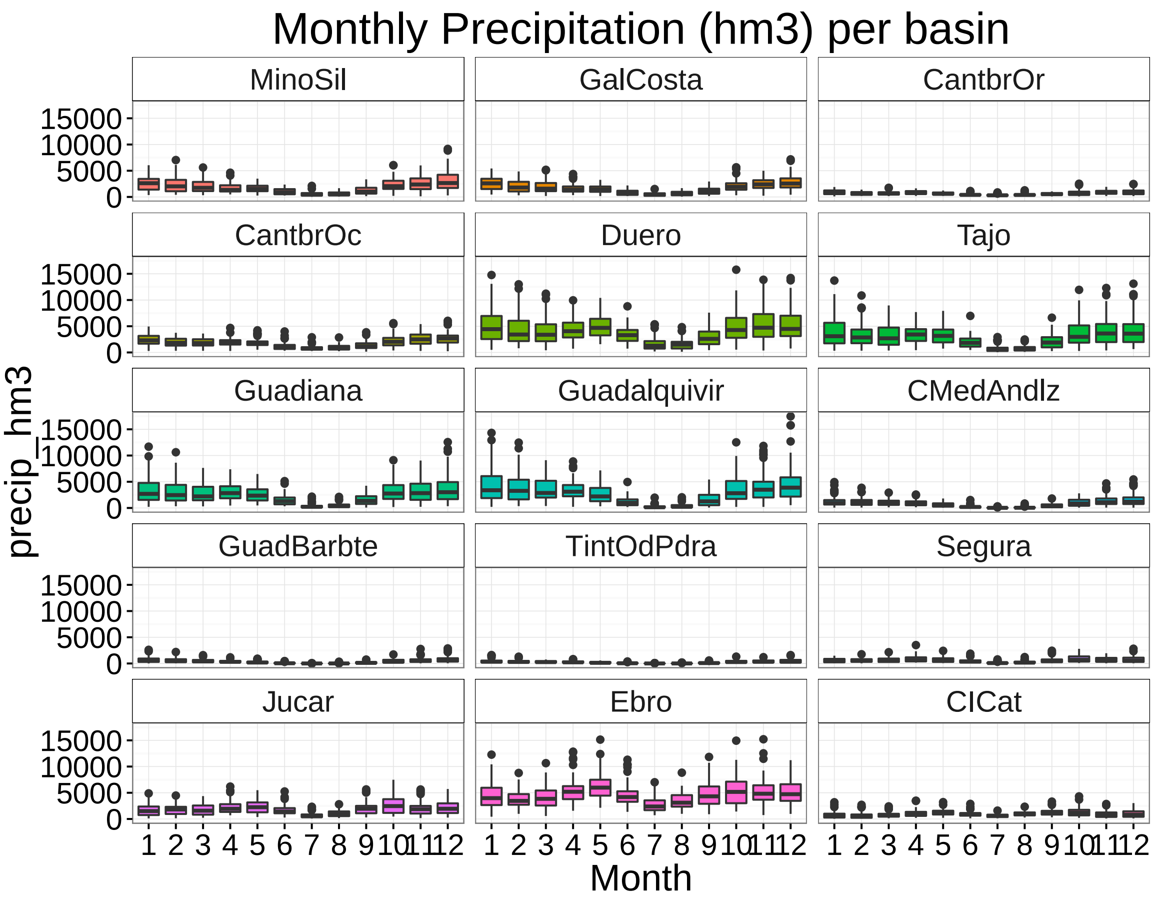

Figure 2.5: Precipitation in hm3 boxplot 1941-2010

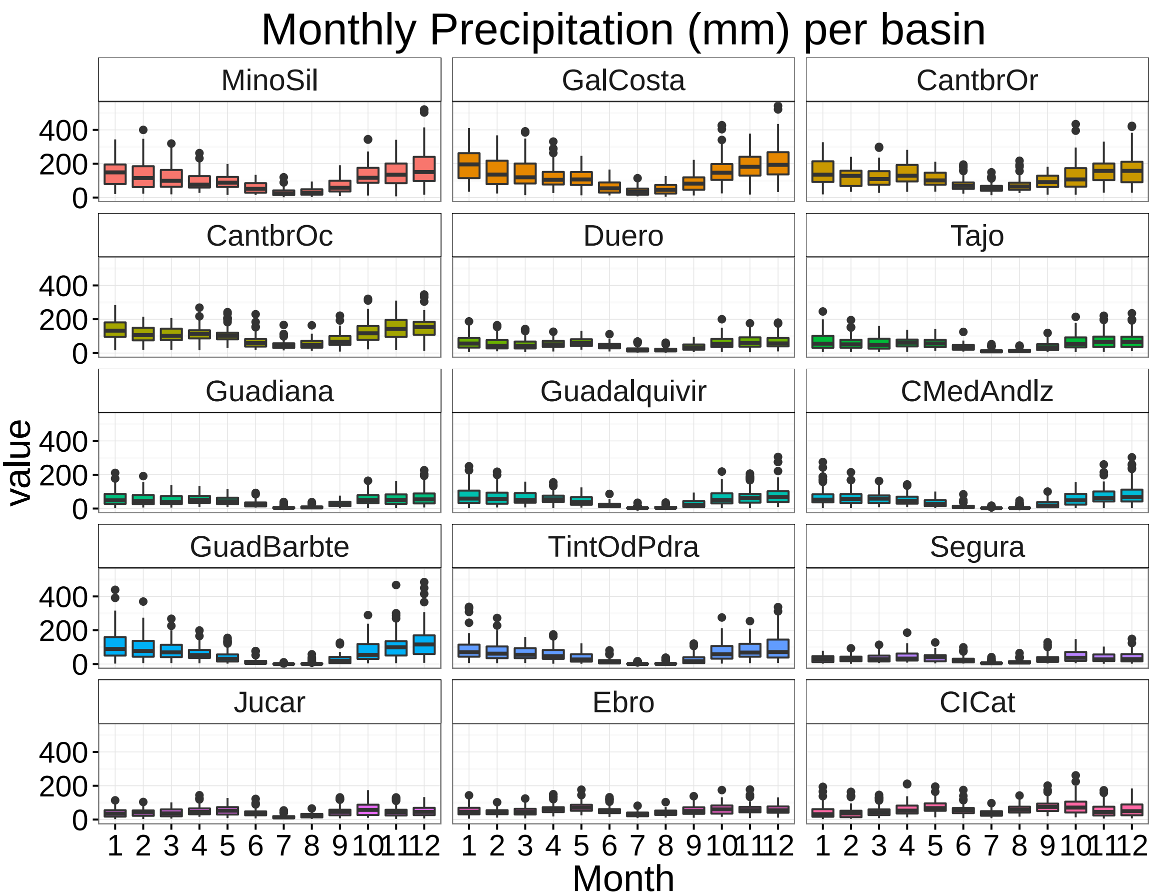

Figure 2.6: Precipitation in mm boxplot 1941-2010

Snow Reserves

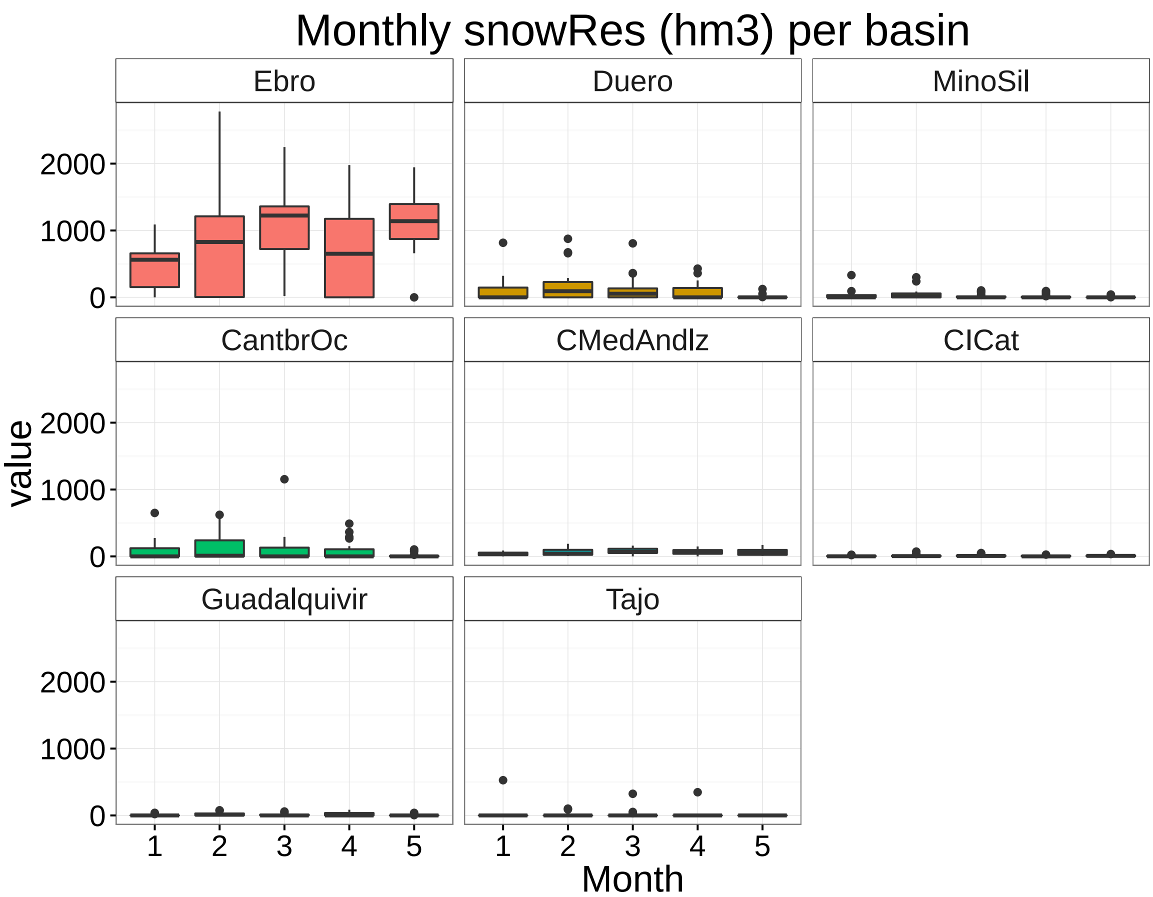

Figure 2.7: Snow reserves in hm3 boxplot 1941-2010

Soil Moisture

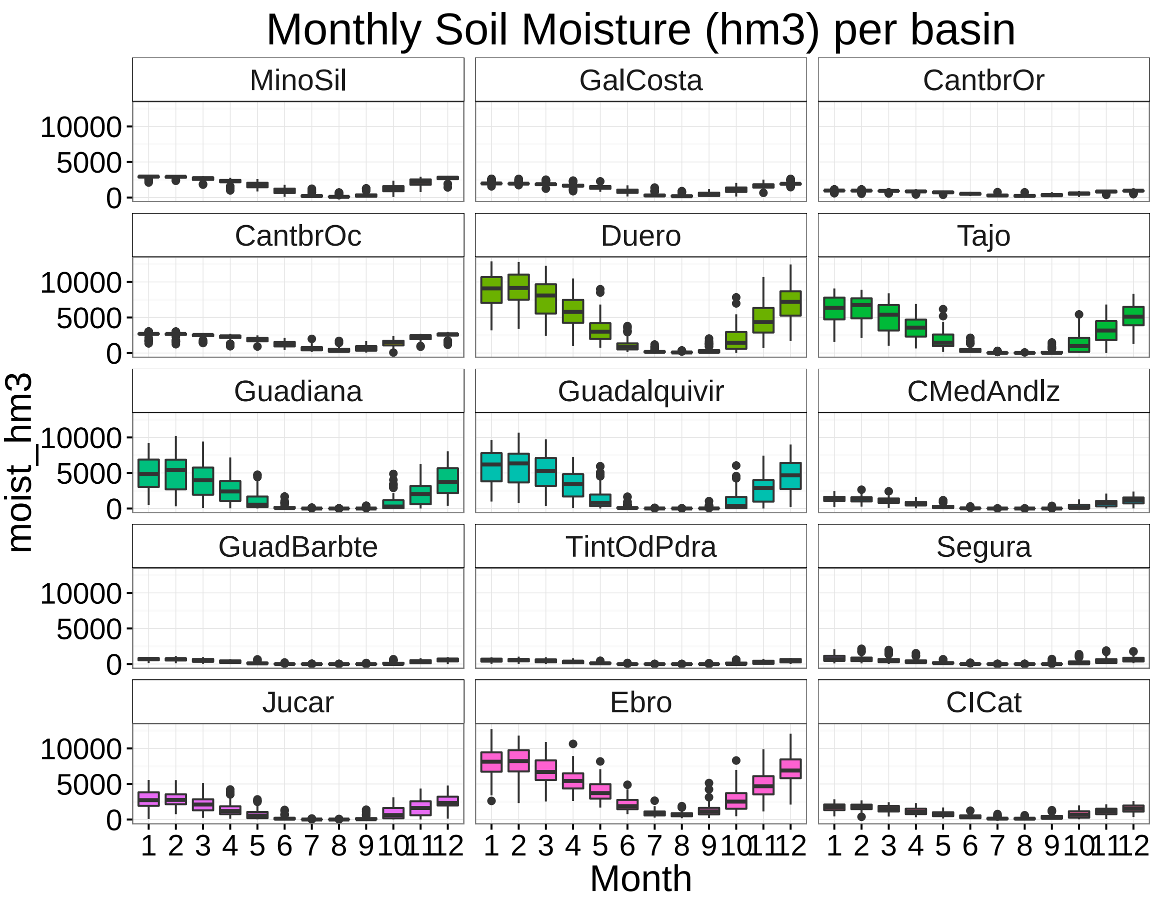

Figure 2.8: Soil moisture in hm3 boxplot 1941-2010

Evapotranspiration Potential

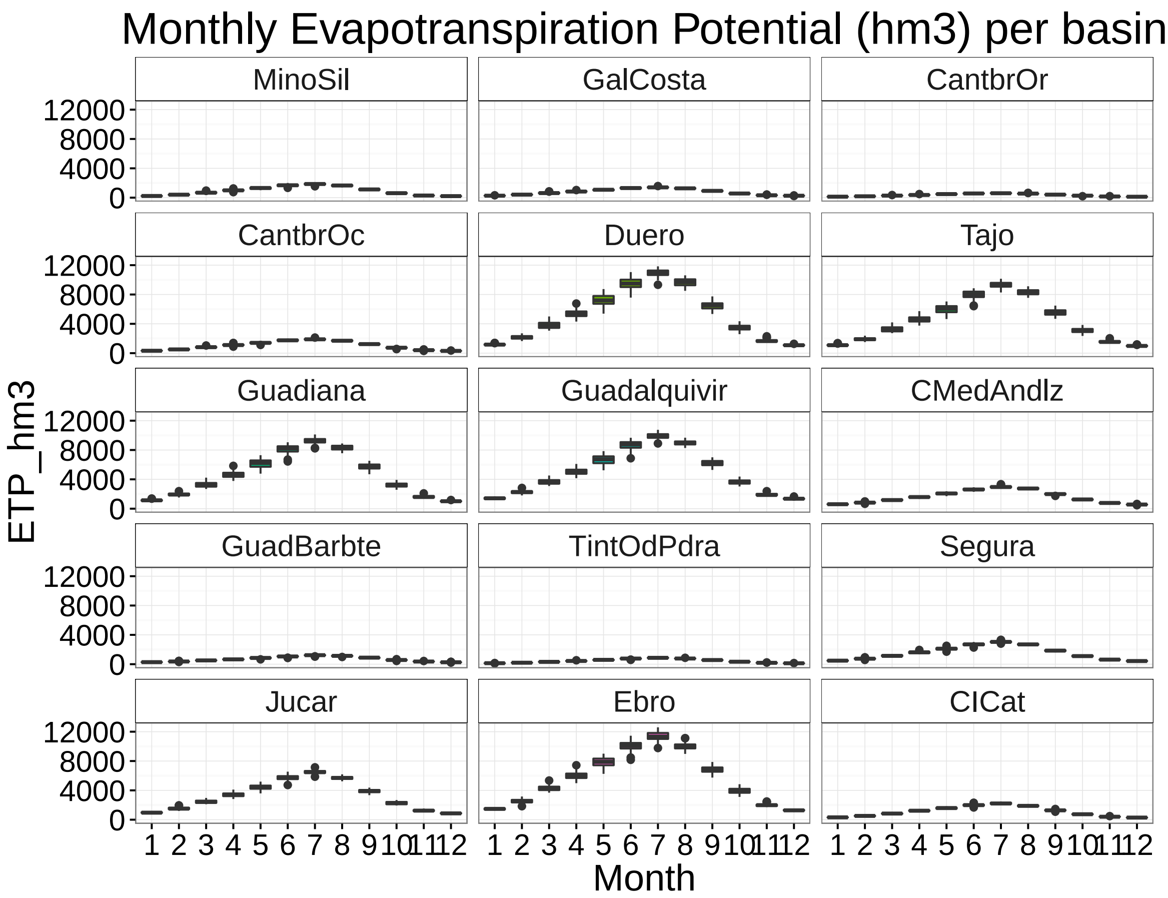

Figure 2.9: Evapotranspiration Potential in hm3 boxplot 1941-2010

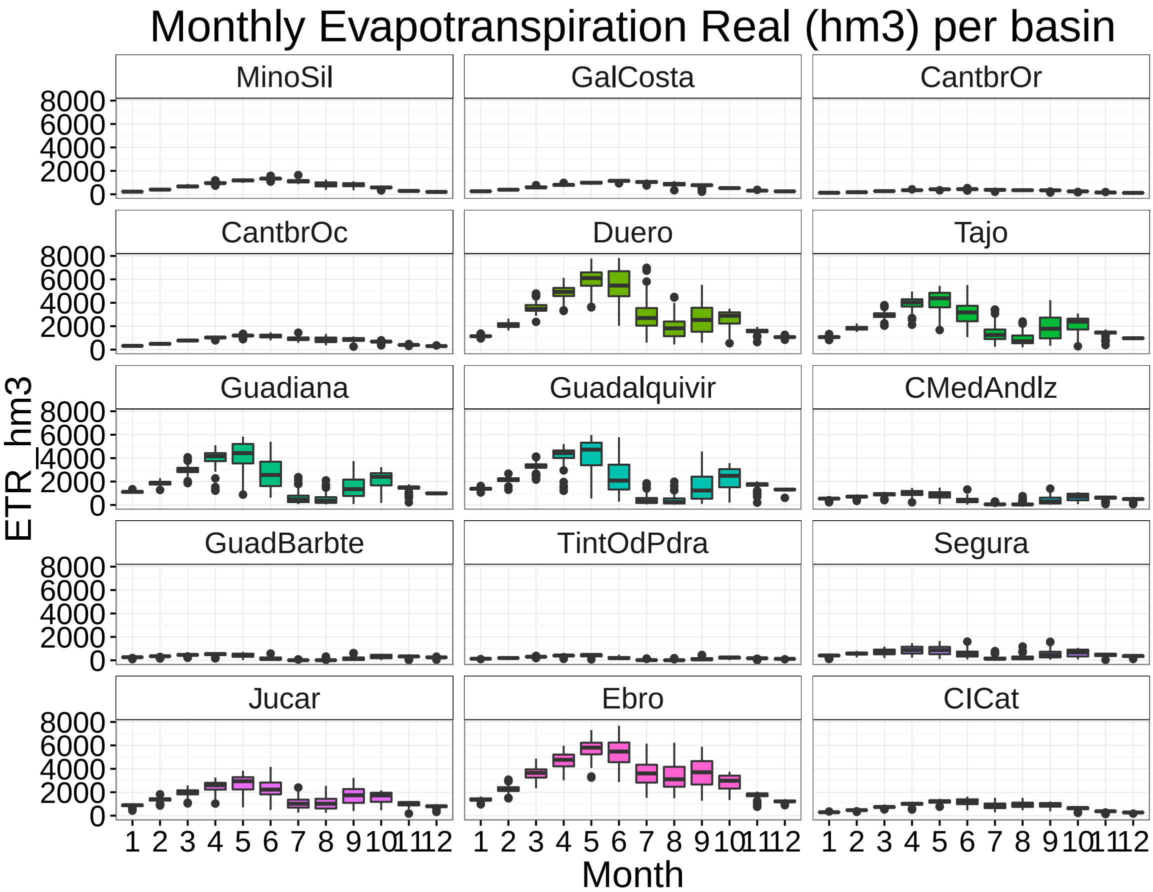

Figure 2.10: Evapotranspiration Real in hm3 boxplot 1941-2010

Runoff

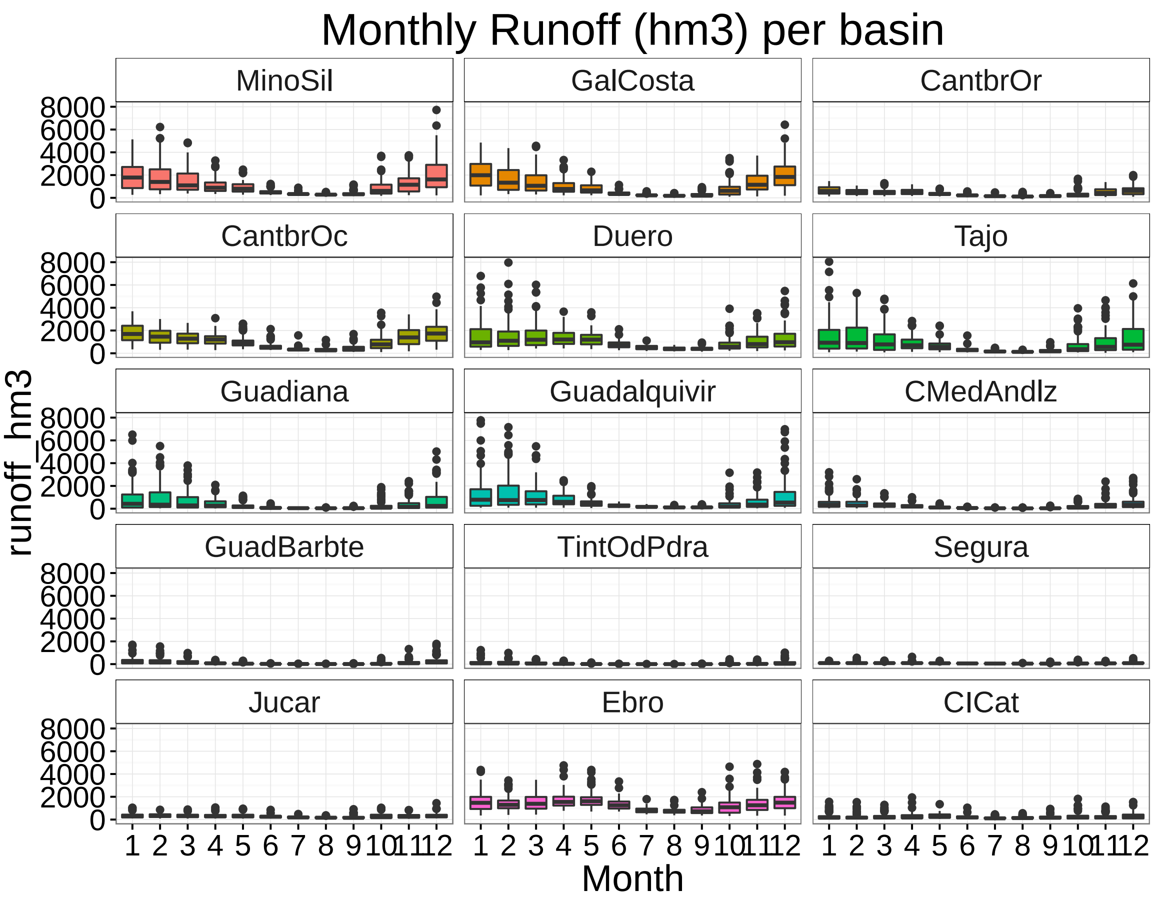

Figure 2.11: Runoff in hm3 boxplot 1941-2010

2.5 Future Predictions and Climate Change

Chapter 3

Rainwater harvesting

3.1 Key Points

3.2 Introduction

UNEP 2001 gdrcRWH [3] Rainwater harvesting provides a decentralized, environmentally sound alternative to augment physical freshwater supplies. Rainwater harvesting is a relatively simple technology with evidence showing the technology in use dating back to early Roman times since atleast 2000 BC. The technology consists of using rooftops, land surfaces or rock catchments combined with conveyance systems to direct rainwater into jars, pots or other storage tanks for later use. These three components catchment, conveyance and storage define a rainwater harvesting system. Rainwater in general has a good quality standard, close to that of WHO drinking standards, however, depnding on the region and type of system acid rain can cause low pH levels and bird and rodent droppings can contaminate the water. Harvested rain water is often used to offset potable water demand by using it for non-potable purposes such as toilet flushing, garden irrigation and in washing machines.

Materials for catchment areas should be non'toxic and are usually built from concrete, aluminum, galvanized iron, fibreglass shingles, slate and other such materials. Painting or coating is not recommended since toxic paint could wash off into the water. Conveyance systems usually comprise of collection devices such as rooftop gutters connected to down'pipes leading to the storage tanks. Pipes should be made of PVC or an inert substance to avoid the risk of corrosion from low pH rainwater. Gutters and pipes need to be periodically cleaned and inspected for leaks. Storage tanks vary in size and can be underground or overground. The construction material should be inert and is often reinforced concrete, fibreglass, polyethylene or stainless steel. Tanks need to be cleanable and should be covered to avoid sunlight leading to the growth of algae. A coarse inlet filter is also recommended to exclude debris, dirt, leaves and other oslid materials. When it first starts to rain, dirt and debris will be washed into the conveyance system and this initial volume needs to be diverted out of the storage system.

EA2010rwh [4] The amount of rain water collected can be calculated as shown in Equation 3.2.1 [4] in which V is the volume of water collected (mm^3), R is the rainfall (mm), A is the the effective area (mm^2) (plane horizontal area when looking straight down at roof), d is the drainage coefficient (%) (estimated at 0.9 for a pitched roof and 0.8 for pitched roof with tiles or for a flat roof with a gravel layer) and f is the filter efficiency (%) (estimated at about 0.9). The size of the tank is recommended to be 5% of the estimated annual volume.

$$V = R * A * d * f \tag{3.2.1}$$

For lack of data, existing capacity of rainwater harvesting in Spain is not estimated and will be taken as 0. A rough estimate of total rainwater harvesting potential is calcualted using the predicted total artificial surface land cover from the 2006 CORINE land use data set [5]. Artifical land cover is estimated at 2% of the total area of approximately 500,000 km^2. From Equation 3.2.1 we can then estimate the potential rainwater harvesting per year by multiplying with the average annual rainfall of 800 mm giving:

$800/100000$ (mm) x $500000x100x0.02$ (hm^2) x 0.9 x 0.9 = $6,500$ hm^3.

The Environment Agency from the UK [4] estimates rainwater harvesting systems can cost between 2,500 to 6000 GBP (2,975 to 7,140 €) depending on the size of the plant.

Energy use will be directly effected by the location of the storage tank and the required pumping. Operational energy use is estimated to be between 0.6 to 5 kWh/m^3 without ultraviolet disinfection and upto 7 kWh/m^3 with UV disinfection [4].

The benefits of rainwater harvesting are often calculated by considering the costs saved by reduction in mains water supply. This then means that the pay-back period is strongly connected to the original main water supply costs. A study from the UK [6] shows payback periods varying from between 4.6 for the county of Devon, where water prices are approximately 3.7 GBP/m^3 to 24 years in Somerset county where the water price is approximately 2.3 GBP/m^3.

Australia 2012 (pdf 18) [7] Data is given for the most rpofitable scenario which involves a Non-BASIX (Australian Building Sustainability Index) compliant four-floor case built on a site area of 4,000 m^2. a 75 m^3 tank with an estimated lifetime of 60 years is used in the case study. The best case is also found when the mains water price is 1.643 AUS/kL at 4.5% inflation rate and an interest rate of 5%. Cost benefit ratio is 1.39 resulting in a payback in 38 years. This scenario shows water savings of about 500 kL per year, giving a total water savings of about 30,000 kL over 60 years. Table 3.1.

Table 3.1: Cost parameters for rain water harvesting system. Adapted from Rahman 2012 [7]

Parameter	Unit	Value
AUS to EUR	-	0.68
Life	yrs	60
Tank Volume	m^3	75
Site Area	m^2	4,000
Mains Water Price	€/m^3	1.12
Inflation rate	%	0.04
Interest rate	%	0.05
Payback time	yrs	38
Cost Benefit ratio	-	1.39
Life cycle capital cost	€	23,511
Life cycle maintenance cost	€	6,375
Amortization	$P \times (i + i/((1+i)^n - 1))$	-
Annuity for 75 m^3 tank	€/yr	1,242.04
Annuity per tank volume	€/yr/m^3	16.56
Estimated mains water saved	m^3	30,000
Maintenance Cost per m^3	€/m^3	0.21

Another study from 2011 [8] studies rainwater harvesting systems in the municipality of Sant Cugat del Vallés in Spain. Table 3.2 summarizes some of the parameters and related estimates for different capital costs of tank sizes. Table 3.2 summarizes some other parameters for rain water harvesting systems for single and multiple family buildings.

Table 3.2: Capital cost parameters for rain water harvesting tank units. Adapted from domenech 2011 [8]

Parameter	Tank Size	Capital Cost (€)	Amortized (20 yr) €/m^3/yr	Amortized (40 yr) €/m^3/yr	Amortized (60 yr) €/m^3/yr

Interest rate (%)	-	-	0.04	0.04	0.04
Life time (yrs)	-	-	20	40	60
	5	2872	42.27	29.02	25.39
	10	4466	32.86	22.56	19.74
	15	6554	32.15	22.08	19.31
Capital Cost	20	7714	28.38	19.49	17.05
	30	10150	24.9	17.09	14.95
	40	12470	22.94	15.75	13.78
	50	12644	18.61	12.78	11.18

Table 3.3: Parameters for rain water harvesting system. Adapted from domenech 2011 [8]

Parameter	Units	Single family house	Multi family building
Rooftop Area	m^2	107	625
Run-off coefficient	-	0.85	0.85
Number of residents	-	3	42
Toilet demand	Litres per Capita per Day	27	30
Laundry demand	Litres per Capita per Day	16	16
Garden size	m^2	200	300
Garden demand winter	Litres per day	46	69
Garden demand spring	Litres per day	146	219
Garden demand summer	Litres per day	529	793
Garden demand autumn	Litres per day	23	34
Installation	€	700	700
Pump (garden)	€	750	750
Pump (toilet/laundry)	€	750	2000
Piping (toilet/laundry)	€	300	1200
Filter	€	400	400
Maintenance	€/yr	50	300

Bactchelor 2012 investigates cost parameters from some African countries. A summary of some of the parameters are shown in Table 3.4 [9]. The annualized costs are based on a life span of 20 years. It should be careful to that the annualized cost per m^3 are based on the storage volume and not the volume of water produced from rainwater harvesting. Thus this cost per unit volume should not be compared to water prices. Original prices were in USD from 2008, and have been adjusted for inflation and covnerted to the €.

Table 3.4: Rain water harvesting system costs. Adapted from [9]

RWH system	Location	Tank size (m^3)	CapEX (2012 €)			OpEX (2012 €)		TotalEX (2012 €)
			Total	Annualized	Annualized per m^3	Annual	Annual per m^3	Annual per m^3
Stone masonry	Nepal	10	567.53	28.37	2.84	3.67	0.42	3.25
Ferrocement jar	Nepal	6.5	532.47	26.62	4.1	4.67	0.75	4.85
RCC tank	Nepal	60	4782.26	239.09	3.98	7.43	0.17	4.15
Ferrocement tank	Nepal	20	3406.84	170.33	8.52	5.59	0.25	8.77
Sand dam	Ethiopia	400	10135.38	506.72	1.27	-	-	-
Sand dam	Kenya	1750	14994.42	749.65	0.43	74.95	0.04	0.47
Ferrocement jar	Mali	13.6	1158.42	57.92	4.26	-	-	-

Notes:

1. Life span of 20 years was used
2. Annualized costs do not consider interest rates
3. Costs per m^3 are based on the volume of storage rather than that of water supplied
4. 1 USD 2008 = 1.07 USD 2012 considering inflation
5. 1 USD 2012 = 0.78 EUR 2012

Cost estimation for SUDS [10] UK COst estimates

Cost of constructing a Rainwater harvesting System [11] India cost estimate

Generalwater tank-06 [12] cost-benefit analysis not profitable

MastersProject Rainwater harvest 2008 [13] cost-benefit Arlington COunty, Virginia good data

EPA2013P100HOZ [14] general data good

pfc-e 2009 [15] Barcelona gives a budget for harvesting plant

Rhaman 2007 conference [16] summary of costs

Rahman Sustainability of rwharvest 2010 [17] Australia costs and opex

Spain 2011 [18] general

Energy [19] Energy [20]

3.3 Parameter Summary

3.4 Worked Example

3.5 Costs

3.6 Energy Consumption

assume rooftop models or using pumping needs from gwpump

3.7 Water Efficiency

3.8 Existing Capacity

0

3.9 Storage

3.10 Future Predictions and Climate Change

Chapter 4

Surface Water and Reservoirs

4.1 Key Points

4.2 Introduction

4.3 Reservoir Volume Data

According to the "Libro Blanco Digital del Agua (LDA)" [21] in April, 2013 the total capacity of reservoirs in Spain was about 56,589 hm^3. The LDA also provides the aggregated volume of water in each river basin on a monthly time from 1987 to 2013. A list of reservoirs from 2007 from the "Centro de estudios Hidrográficos (CEH)" [22] estimates the useful reservoir capacity of Spain at 50,962 hm^3 from 1268 dams. The data from CEH also includes information on the surface area of the reservoirs. Individual reservoir data is also provided by the "Red Oficial de Estaciones de Aforo" (ROEA) [23] system and after aggregating the data for each river basin the total usefule capacity is estimated to be 49,010 hm^3 from 435 dams. The ROEA system has data available from 1958 to 2011. A summary of the number, surface area and volumes of reservoirs from the different sources is compiled in Table 4.1.

Figure 4.1 compares the number of reservoirs accounted for in the CEH and ROEA databases while Figure 4.2 shows the volumes covered. The monthly distribution of the reservoir volumes for each basin from both databases are shown in Figure 4.3 and the combined average in Figure 4.4. Overall annual ranges of reservoir levels for each basin are shown in Figure 4.5. The evolution over the years for the different basins are shown in Figure 4.6 and Figure 4.7. The spatial distribution of the combined average of the ROEA and LDA systems is shown on a monthly basis in Figure 4.8 and annually in Figure 4.9.

The average, minimum and maximum values of the combined ROEA and LDA datasets accounting for data from 1988 to 2012 are shown in Table 4.2, Table 4.3, and Table 4.4 respectively.

Table 4.1: Reservoir data for Spain

Basin	Surface Area hm^2 (CEH)	No. of Reservoirs (CEH)	No. of Reservoirs (ROEA)	Vol. of Reservoirs hm^3 (CEH)	Vol. of Reservoirs hm^3 (ROEA)	Vol. of Reservoirs hm^3 (LDA)
Duero	34,872	87	30	6,887	6,849	7,507
Segura	7,045	37	18	1,174	1,138	1,141
Tajo	57,021	298	57	10,801	10,775	11,012
Jucar	17,099	51	32	3,102	3,101	3,336
Ebro	42,211	212	98	6,327	6,052	7,602
CICat	2,525	14	10	747	743	740
MinoSil	1,730	58	35	2,718	2,717	3,030
GalCosta	4,381	24	11	592	592	684
CantbrOc	2,208	36	32	468	456	554
CantbrOr	659	34	3	65	22	100
Guadiana	86,494	175	30	8,731	7,668	9,435
TintOdPdra	2,976	57	1	131	58	229
Guadalquivir	37,679	118	59	6,820	6,628	8,391
GuadBarbte	11,232	22	8	1,209	1,209	1,651
CMedAndlz	5,685	45	11	1,190	1,002	1,177
Total	313,817	1,268	435	50,962	49,010	56,589

CEH: Centro de estudios Hidrográficos [22]
ROEA: Red Oficial de Estaciones de Aforo [23]
LDA: Libro Blanco Digital del Agua (LDA) [21]

Table 4.2: Monthly average combined reservoir volumes (hm^3) from CEH [22] and ROEA [23] systems

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GalCosta	306.00	337.00	394.00	404.00	395.00	380.00	328.00	333.00	360.00	368.00	374.00	342.00
MinoSil	1050.00	1126.00	1218.00	1274.00	1300.00	1250.00	1148.00	1068.00	1026.00	991.00	1039.00	1046.00
CantbrOc	339.00	367.00	413.00	423.00	414.00	404.00	368.00	371.00	383.00	381.00	371.00	358.00
CantbrOr	36.00	41.00	47.00	52.00	51.00	48.00	42.00	44.00	48.00	48.00	48.00	42.00
Duero	4110.00	4394.00	5166.00	5338.00	5140.00	4760.00	4246.00	4199.00	4488.00	4569.00	4410.00	4274.00
Tajo	5578.00	5897.00	6565.00	6775.00	6617.00	6219.00	5816.00	5812.00	6100.00	6192.00	6050.00	5788.00
Guadiana	4005.00	4245.00	4770.00	5026.00	4955.00	4693.00	4525.00	4602.00	4966.00	5140.00	5119.00	4544.00
TintOdPdra	79.00	83.00	94.00	99.00	99.00	96.00	86.00	90.00	99.00	105.00	106.00	92.00
Guadalquivir	3215.00	3452.00	4031.00	4294.00	4239.00	3988.00	3727.00	3776.00	4168.00	4308.00	4322.00	3760.00
GuadBarbte	585.00	630.00	722.00	774.00	773.00	723.00	698.00	728.00	794.00	849.00	855.00	727.00
CMedAndlz	237.00	271.00	327.00	347.00	337.00	311.00	294.00	321.00	362.00	384.00	358.00	288.00
Segura	541.00	578.00	719.00	762.00	710.00	637.00	595.00	616.00	719.00	752.00	725.00	624.00
Jucar	1281.00	1440.00	1703.00	1742.00	1657.00	1546.00	1394.00	1453.00	1624.00	1623.00	1558.00	1413.00
Ebro	3101.00	3208.00	4023.00	4018.00	3948.00	3797.00	3280.00	3188.00	3710.00	3678.00	3649.00	3414.00
CICat	195.00	201.00	241.00	235.00	221.00	218.00	206.00	210.00	241.00	233.00	215.00	203.00

Table 4.3: Monthly minimum combined reservoir volumes (hm^3) from CEH [22] and ROEA [23] systems

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GalCosta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MinoSil	82.00	82.00	100.00	126.00	109.00	97.00	82.00	82.00	110.00	187.00	167.00	131.00
CantbrOc	189.00	197.00	226.00	306.00	325.00	235.00	179.00	177.00	174.00	214.00	231.00	192.00

Table 4.3: Monthly minimum combined reservoir volumes (hm^3) from CEH [22] and ROEA [23] systems

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CantbrOr	0.00	0.00	0.00	14.00	15.00	0.00	14.00	12.00	9.00	6.00	0.00	0.00
Duero	2297.00	2197.00	2473.00	3058.00	3058.00	2731.00	2665.00	2315.00	2176.00	2035.00	2246.00	2327.00
Tajo	3356.00	3783.00	4283.00	4264.00	4304.00	4000.00	3356.00	3730.00	3484.00	3372.00	3585.00	4272.00
Guadiana	737.00	803.00	857.00	839.00	815.00	777.00	737.00	698.00	673.00	645.00	782.00	818.00
TintOdPdra	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guadalquivir	585.00	672.00	788.00	865.00	855.00	793.00	585.00	672.00	749.00	737.00	780.00	821.00
GuadBarbte	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CMedAndlz	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Segura	119.00	109.00	131.00	123.00	125.00	101.00	97.00	88.00	77.00	85.00	93.00	110.00
Jucar	416.00	445.00	470.00	451.00	395.00	353.00	299.00	232.00	214.00	276.00	281.00	349.00
Ebro	1461.00	1402.00	1776.00	1293.00	2448.00	2399.00	2050.00	1677.00	1469.00	1030.00	1102.00	1594.00
CICat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4.4: Monthly minimum combined reservoir volumes (hm^3) from CEH [22] and ROEA [23] systems

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GalCosta	534.00	515.00	634.00	634.00	634.00	634.00	634.00	634.00	634.00	634.00	634.00	575.00
MinoSil	2620.00	2611.00	2708.00	2653.00	2528.00	2427.00	2391.00	2266.00	1907.00	2087.00	2330.00	2566.00
CantbrOc	437.00	461.00	512.00	511.00	511.00	511.00	511.00	511.00	511.00	511.00	511.00	458.00
CantbrOr	81.00	78.00	89.00	89.00	90.00	89.00	89.00	89.00	89.00	89.00	90.00	81.00
Duero	6638.00	6584.00	6918.00	7053.00	6874.00	6738.00	5882.00	5458.00	6851.00	7053.00	6618.00	6078.00
Tajo	8257.00	8380.00	8595.00	8617.00	8579.00	8489.00	8191.00	8191.00	8430.00	8599.00	8362.00	8517.00

Table 4.4: Monthly minimum combined reservoir volumes (hm^3) from CEH [22] and ROEA [23] systems

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Guadiana	7446.00	7756.00	8419.00	8419.00	8419.00	8419.00	8419.00	8419.00	8419.00	8419.00	8419.00	7588.00
TintOdPdra	180.00	186.00	212.00	223.00	225.00	225.00	210.00	210.00	212.00	223.00	225.00	195.00
Guadalquivir	6292.00	6864.00	7877.00	7877.00	7877.00	7922.00	7922.00	7928.00	7928.00	7928.00	7928.00	7036.00
GuadBarbte	1353.00	1454.00	1591.00	1591.00	1591.00	1591.00	1591.00	1591.00	1591.00	1591.00	1591.00	1472.00
CMedAndlz	793.00	860.00	965.00	965.00	965.00	965.00	965.00	965.00	965.00	965.00	965.00	879.00
Segura	1612.00	1724.00	1992.00	2000.00	1846.00	1714.00	1634.00	1724.00	1992.00	2000.00	1846.00	1623.00
Jucar	2360.00	2063.00	2778.00	2778.00	2778.00	2778.00	2778.00	2778.00	2778.00	2778.00	2778.00	2480.00
Ebro	4863.00	5075.00	6430.00	6082.00	5782.00	5766.00	5766.00	5766.00	6456.00	6108.00	5808.00	5186.00
CICat	618.00	582.00	659.00	650.00	597.00	623.00	618.00	582.00	659.00	650.00	597.00	542.00

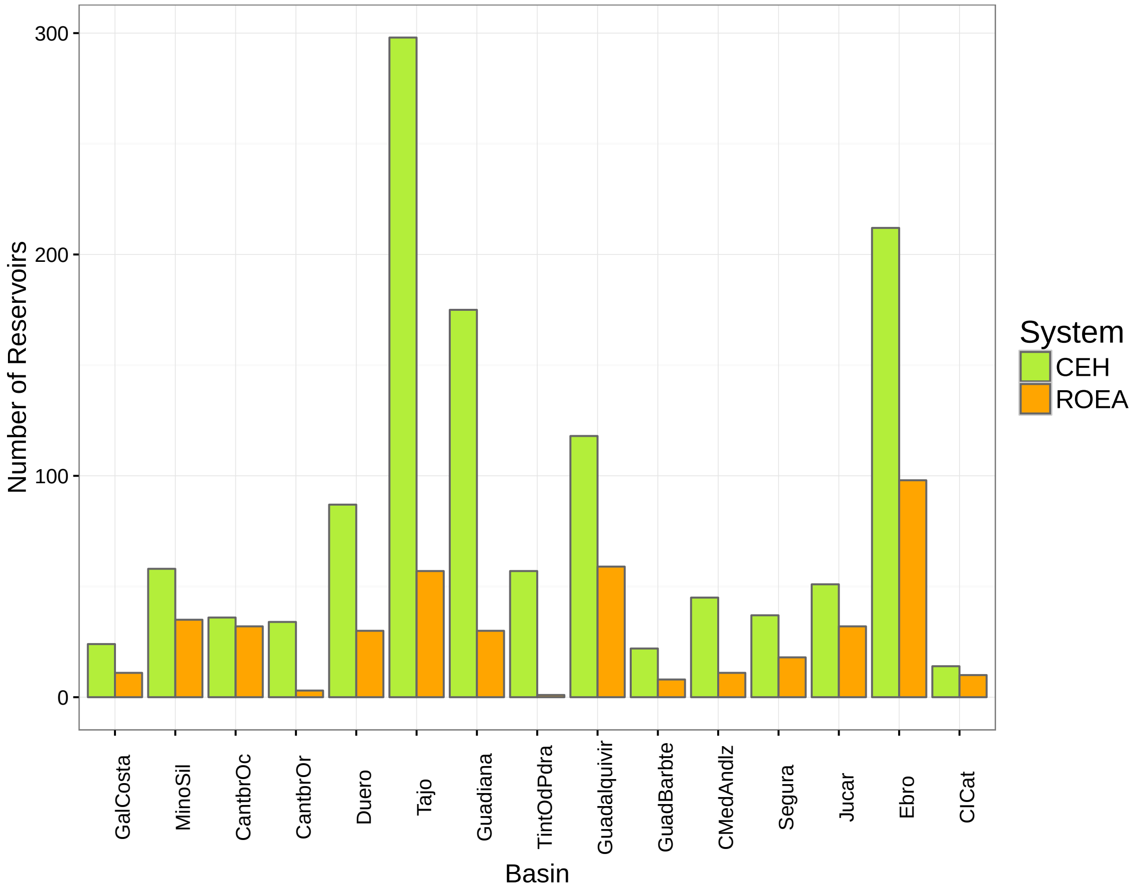

Figure 4.1: Number of reservoirs covered in the CEH [22] and ROEA [23] systems

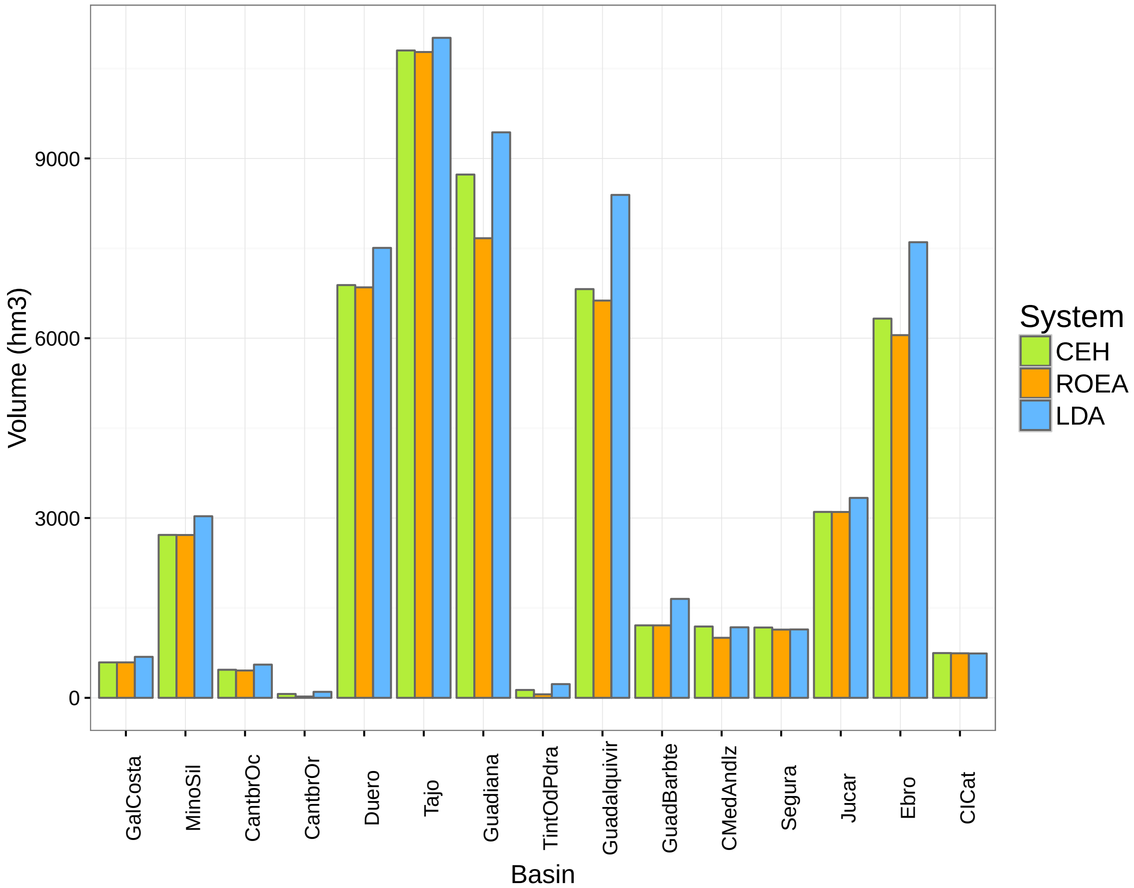

Figure 4.2: Volume of reservoirs covered in the CEH [22], ROEA [23] and LDA [21] systems

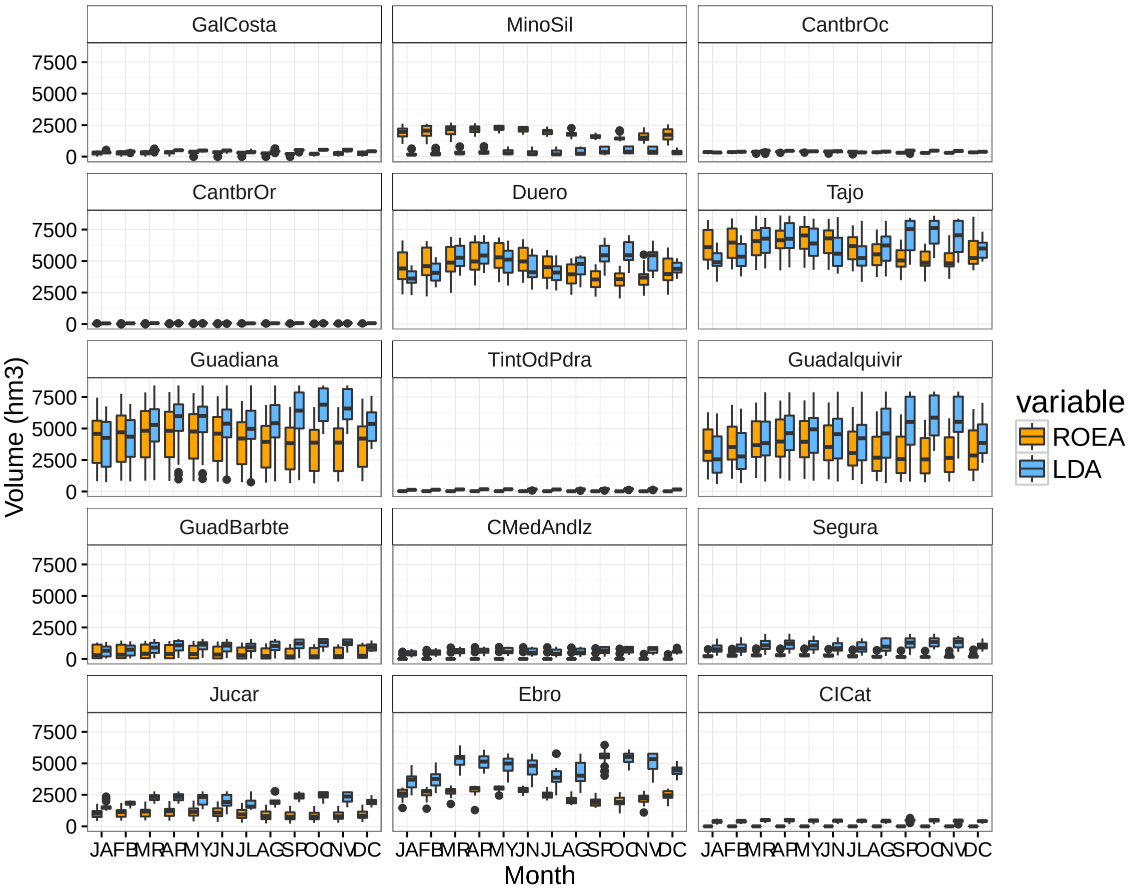

Figure 4.3: Monthly and spatial variation of reservoirs levels in the ROEA [23] and LDA [21] systems (1988-2012)

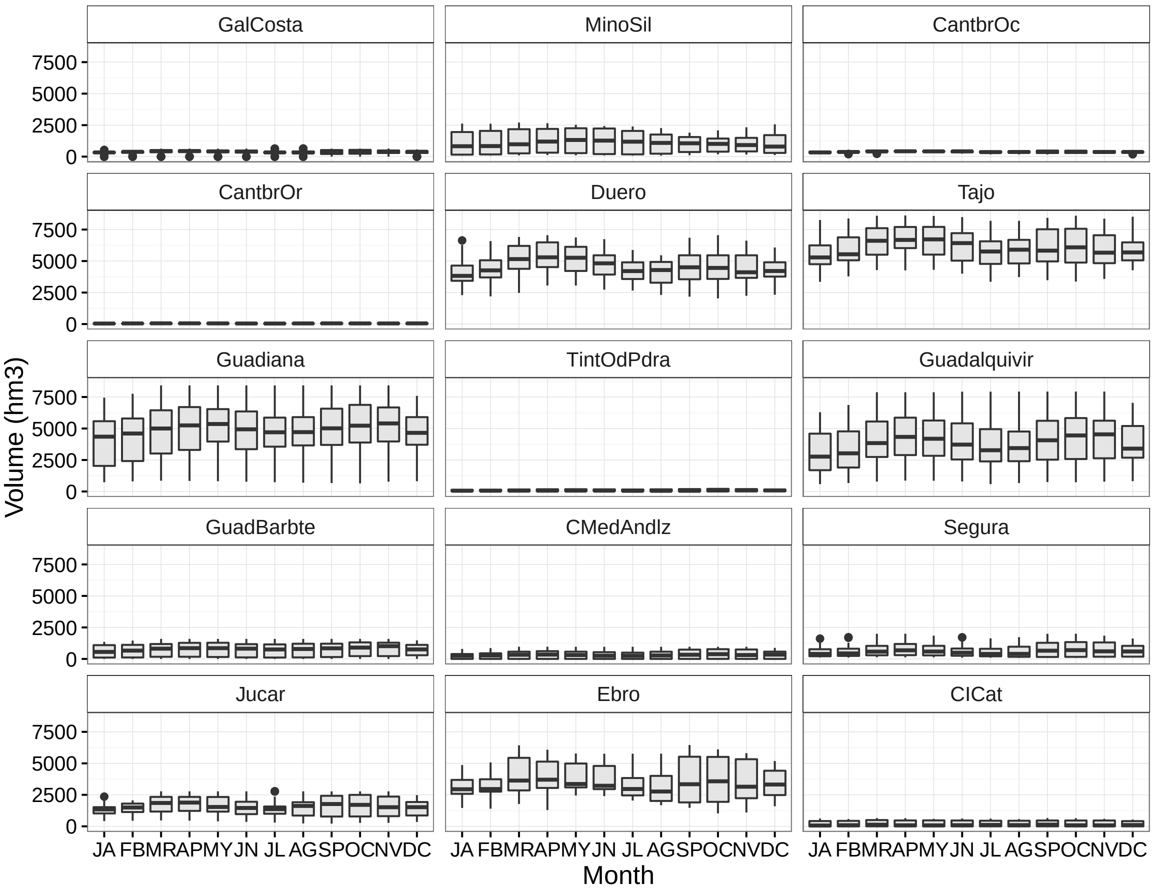

Figure 4.4: Combined monthly and spatial variation of reservoirs levels in the ROEA [23] and LDA [21] systems (1988-2012)

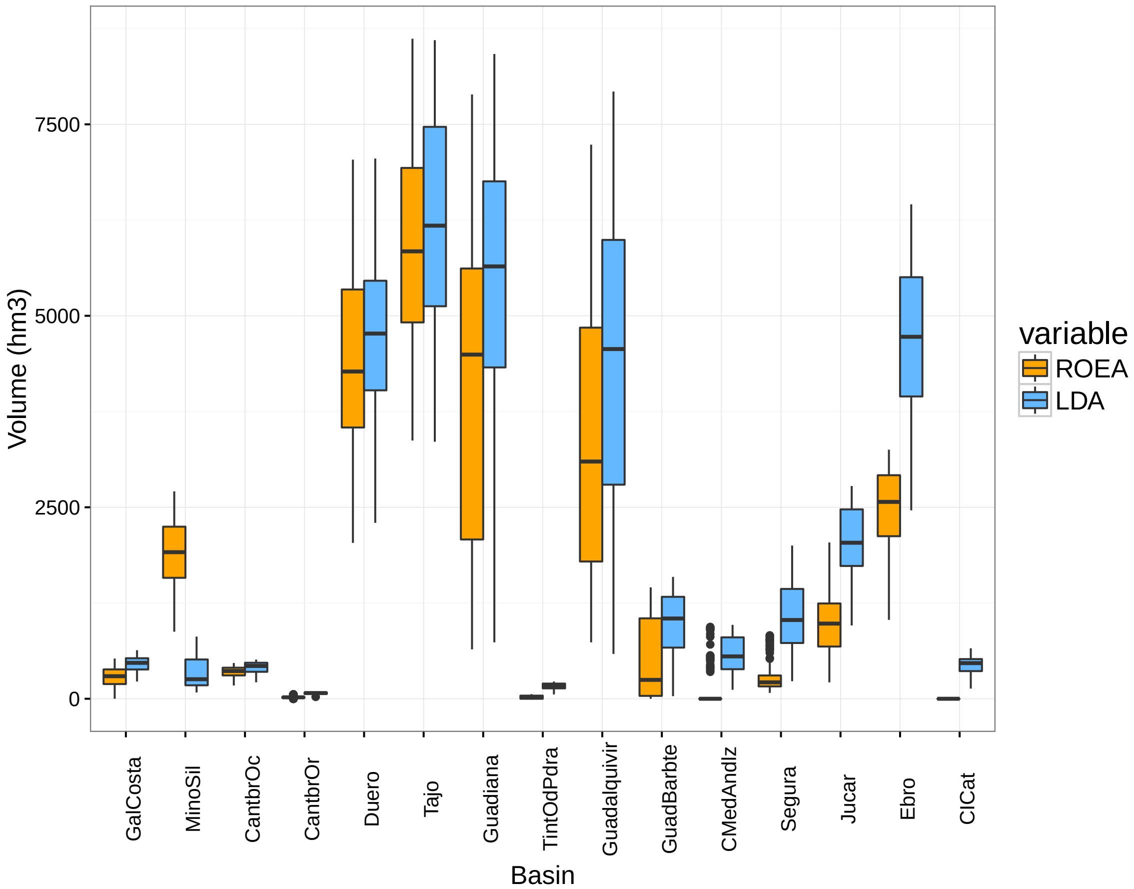

Figure 4.5: Annual variation of reservoirs levels by basin in the ROEA [23] and LDA [21] systems (1988-2012)

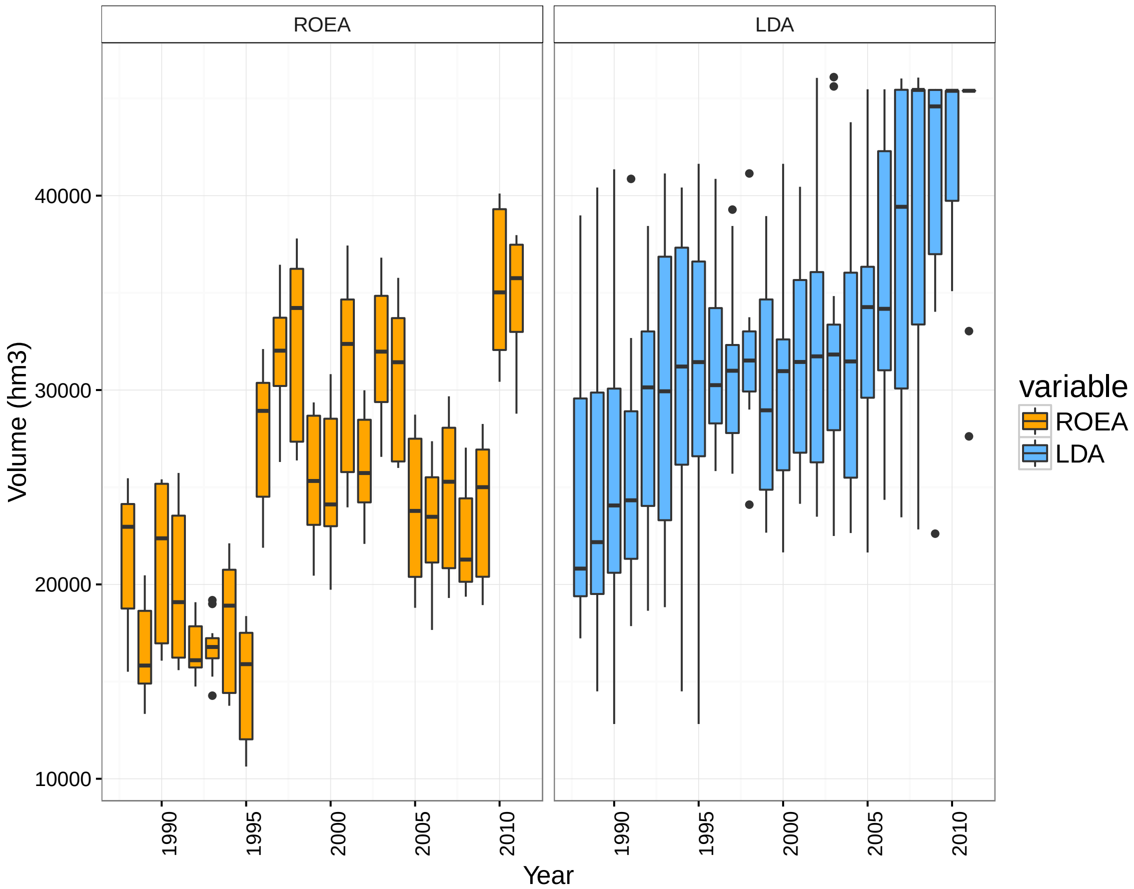

Figure 4.6: Annual evolution of aggregated reservoirs levels in the ROEA [23] and LDA [21] systems (1988-2012)

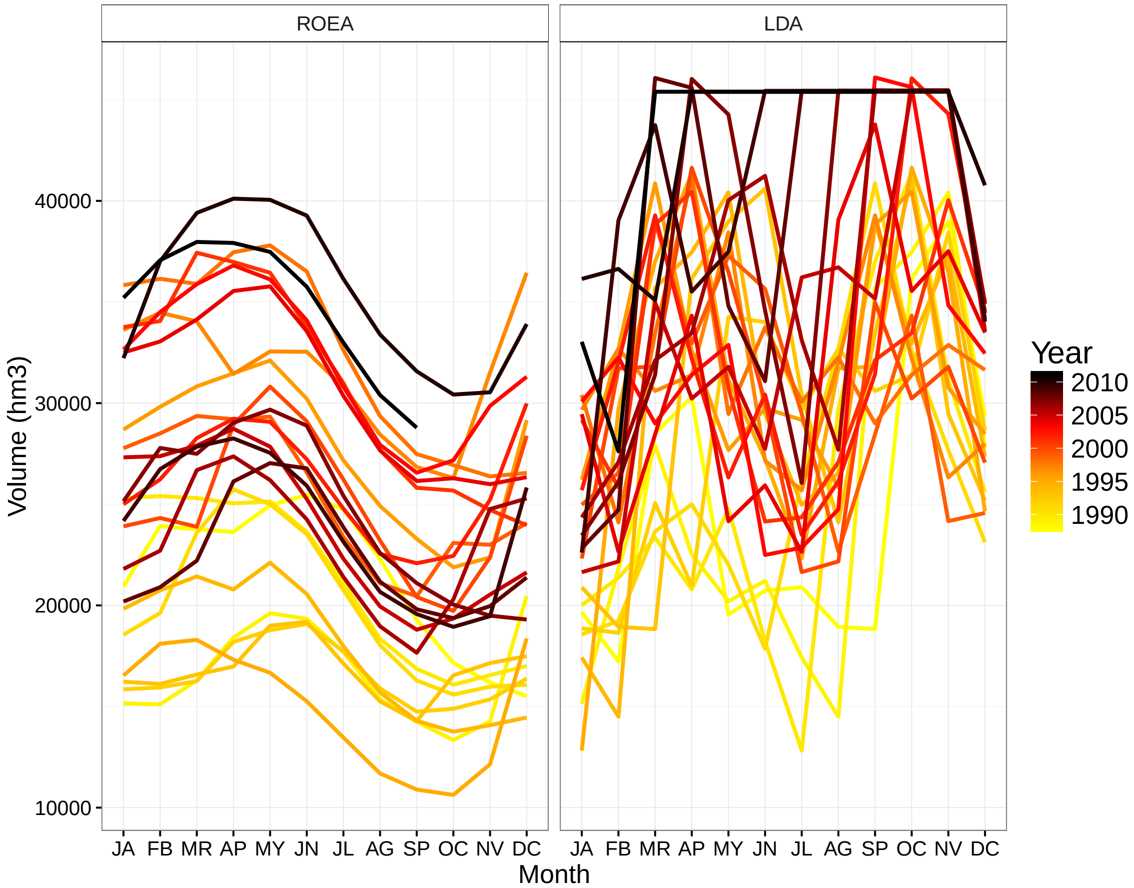

Figure 4.7: Annual evolution of aggregated reservoirs levels by month in the ROEA [23] and LDA [21] systems (1988-2012)

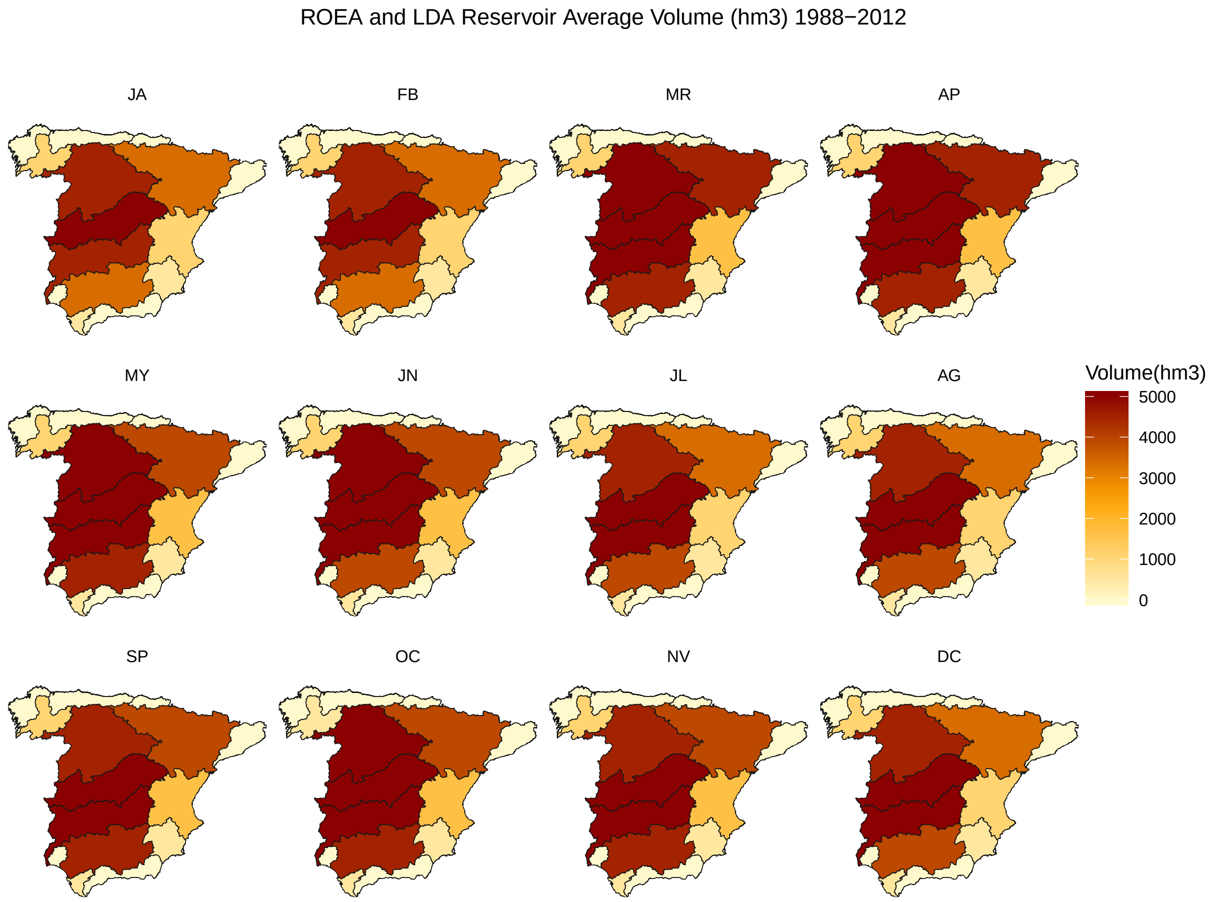

Figure 4.8: Spatial variation of combined average reservoirs levels by month in the ROEA [23] and LDA [21] systems (1988-2012)

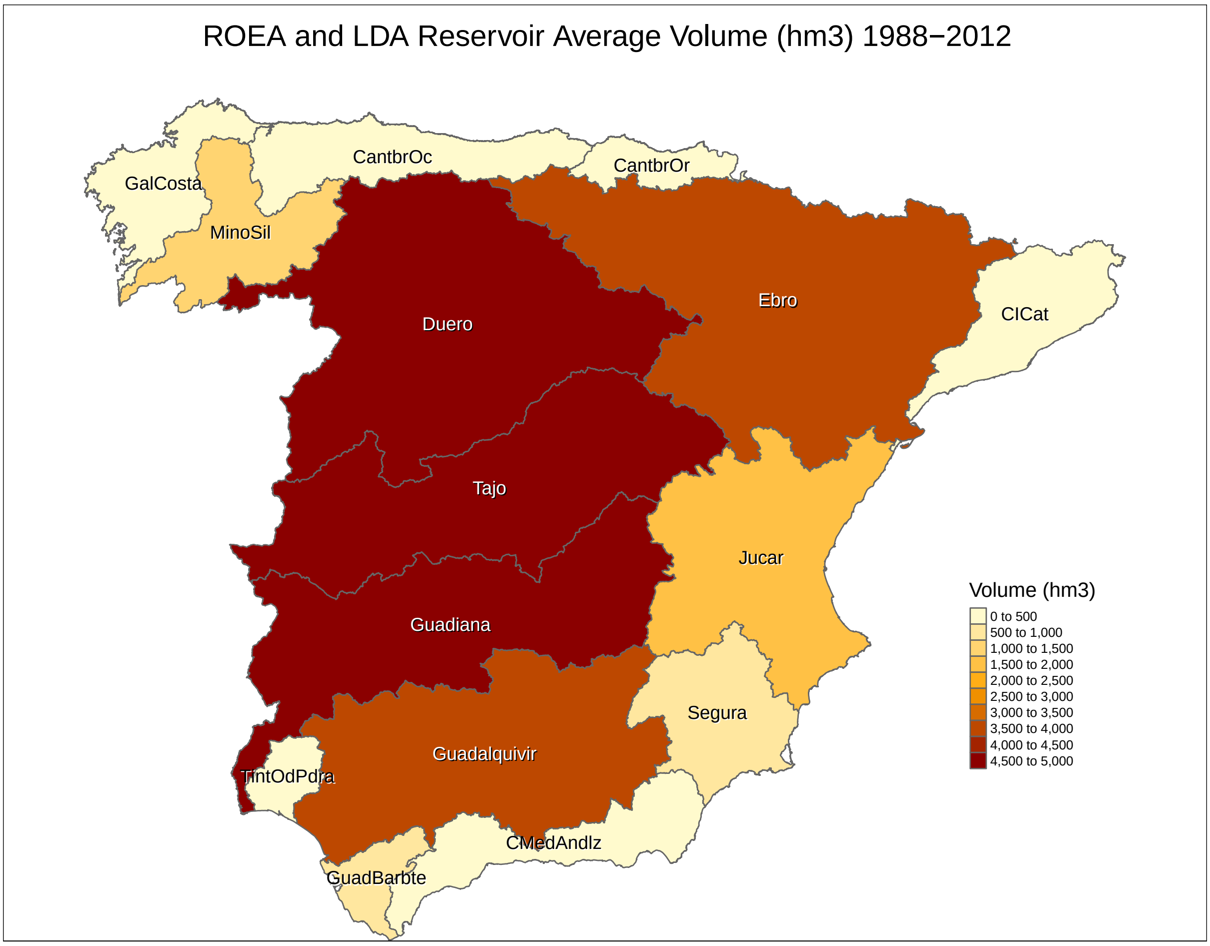

Figure 4.9: Spatial variation of combined annual average reservoirs levels in the ROEA [23] and LDA [21] systems (1988-2012)

4.4 Outflows

The ROEA [23] system also has data for the amount of water flowing out of different reservoirs. The volume covered by the reservoirs for which outflow data is available is compared to the total volume of the reservoirs from the ROEA, CEH and LDA databases. This comparison is shown in Table 4.5 and Figure 4.10 and it can be seen that the records for outflow covers most of the reservoir volume capacity in Spain. Outflow data was available on a monthly basis for each basin from 1958 to 2010. The outflows for each month and basin are shown in Figure 4.11, Figure 4.12 and Figure 4.13. The aggregated data for Spain is shown in Figure 4.14, Figure 4.15 and Figure 4.16. Not surprisingly, basins with high reservoir volume capacity showed high water outflows as well.

Table 4.5: Reservoir volumes (hm^3) for ROEA outflows compared to CEH [22], ROEA [23] and LDA [21] systems

Basin	Vol CEH (hm^3)	Vol ROEA (hm^3)	Vol LDA (hm^3)	Vol ROEA Outflow data (hm^3)	% of LDA
Duero	6886.60	6849.00	7507.00	6849.00	91.23
Segura	1173.50	1138.20	1141.00	1138.20	99.75
Tajo	10800.90	10775.20	11012.00	10775.20	97.85
Jucar	3102.30	3101.00	3336.00	3099.00	92.90
Ebro	6327.20	6051.60	7602.00	6045.20	79.52
CICat	746.90	743.20	740.00	604.20	81.65
MinoSil	2718.20	2716.60	3030.00	2716.60	89.66
GalCosta	591.70	591.60	684.00	559.20	81.75
CantbrOc	468.50	456.00	554.00	455.00	82.13
CantbrOr	64.80	22.00	100.00	25.10	25.10
Guadiana	8730.70	7668.30	9435.00	7668.30	81.28
TintOdPdra	131.30	58.50	229.00	58.50	25.55
Guadalquivir	6819.50	6628.00	8391.00	6641.10	79.15
GuadBarbte	1209.30	1209.00	1651.00	1209.00	73.23
CMedAndlz	1190.20	1001.70	1177.00	1001.70	85.11
Total	50961.60	49009.90	56589.00	48845.30	86.32

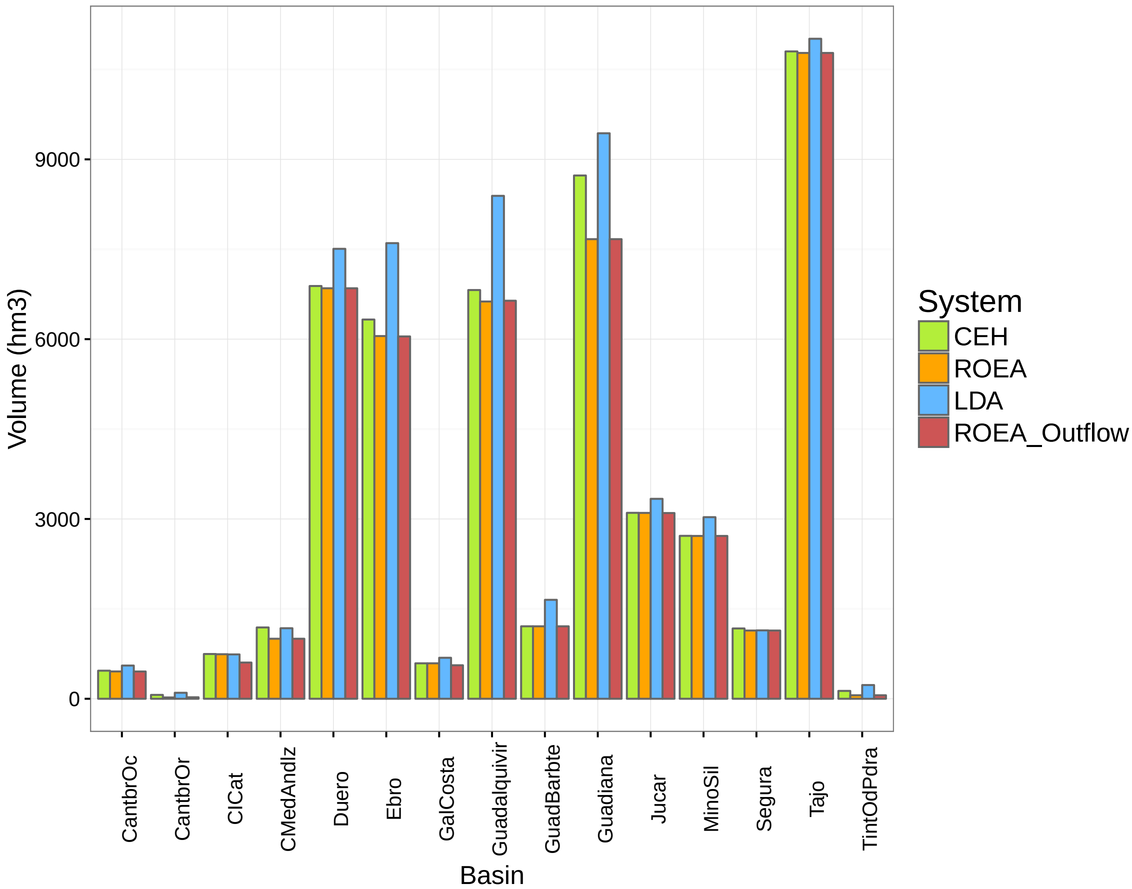

Figure 4.10: Reservoir volumes (hm^3) for ROEA outflows compared to CEH [22], ROEA [23] and LDA [21] systems

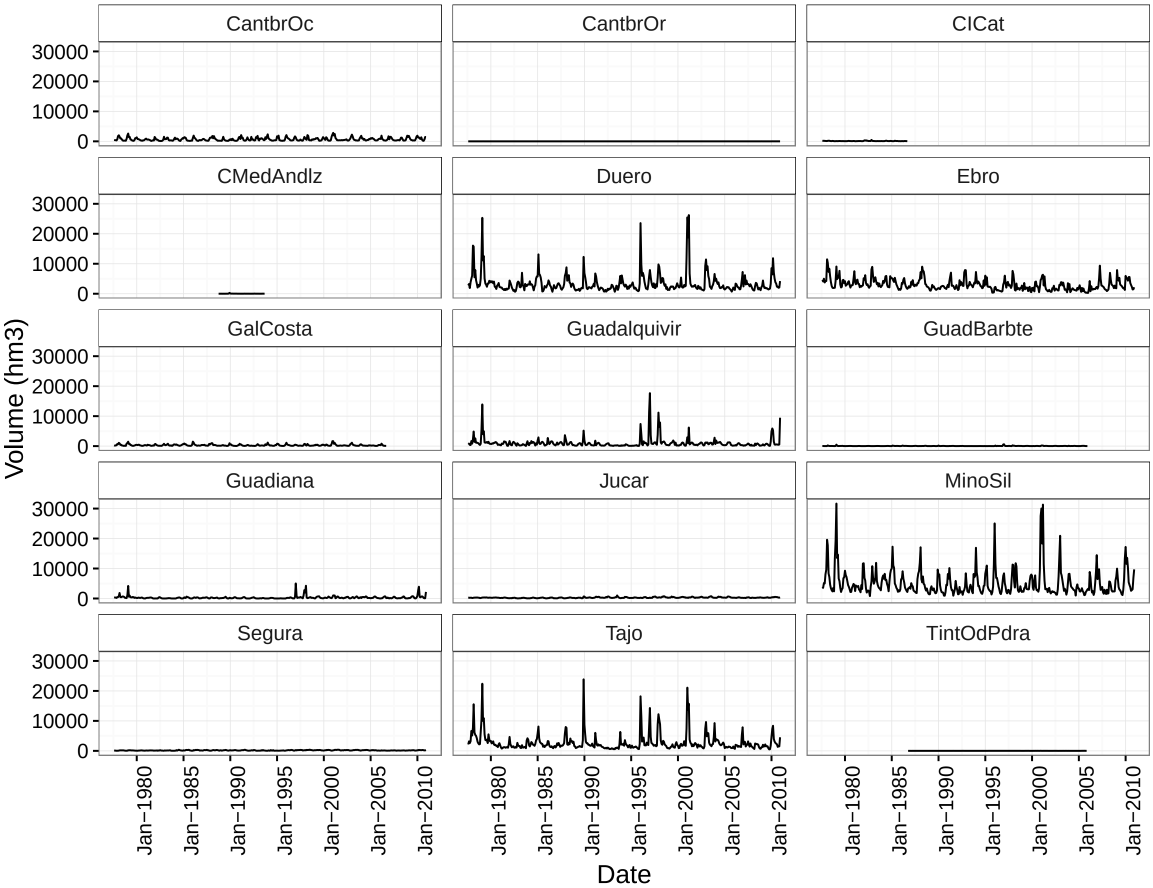

Figure 4.11: ROEA [23] reservoir outflows ($hm^3/month$) by basin historical series

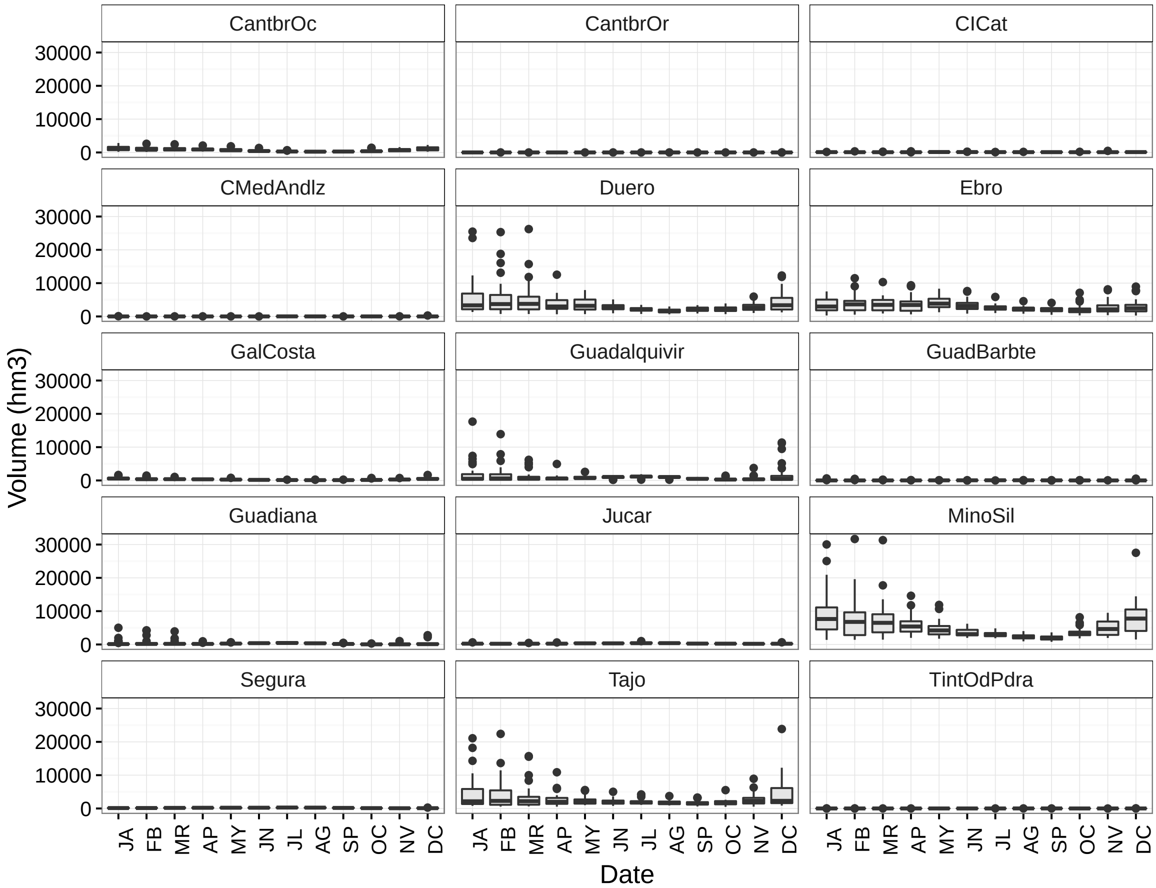

Figure 4.12: ROEA [23] reservoir outflows ($hm^3/month$) by basin boxplot

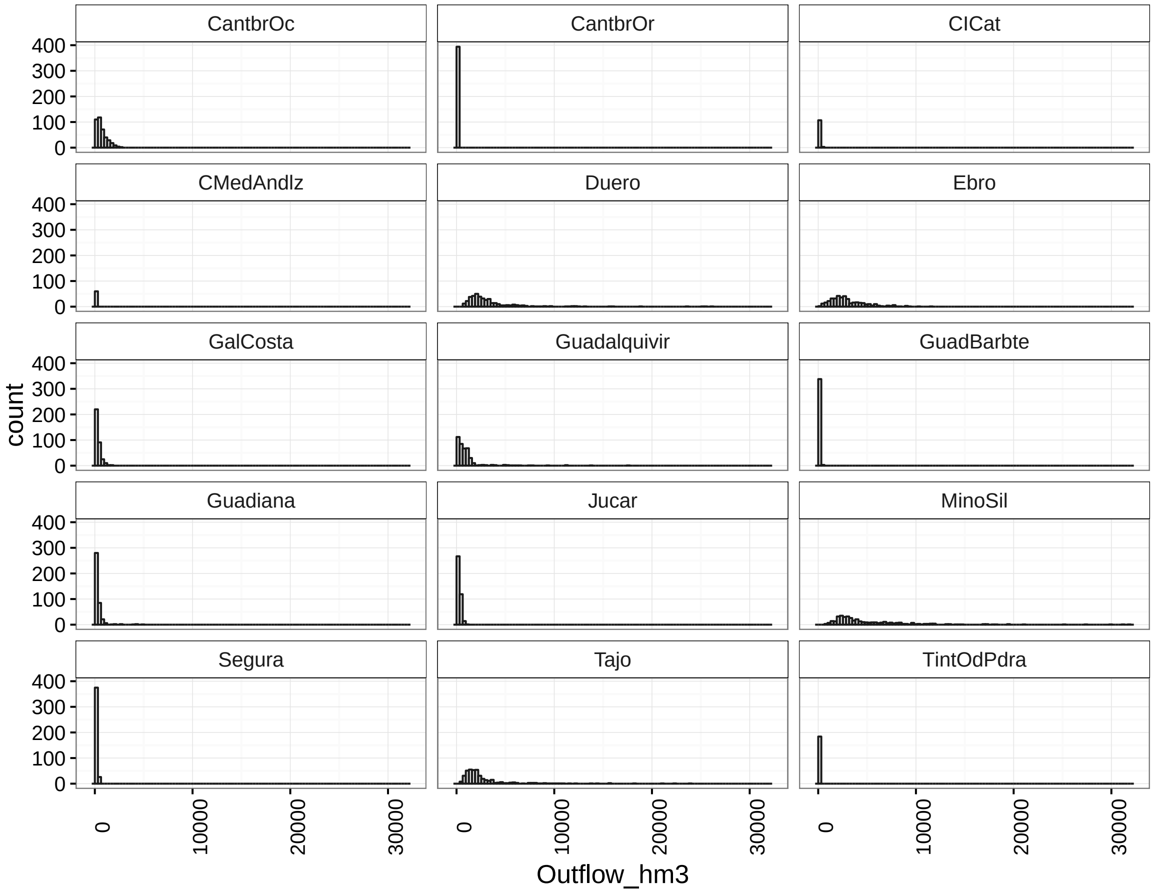

Figure 4.13: ROEA [23] reservoir outflows ($hm^3/month$) by basin histogram

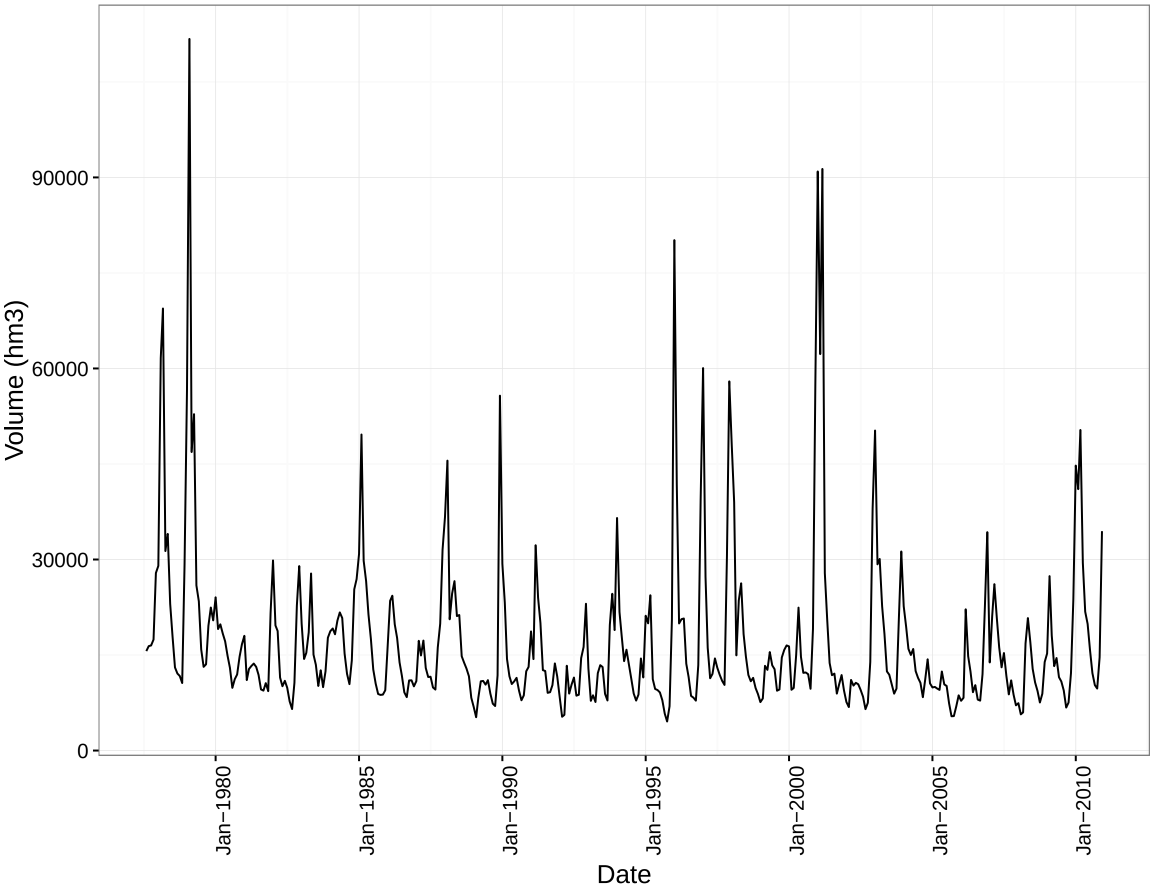

Figure 4.14: ROEA [23] reservoir outflows ($hm^3/month$) by basin historical series

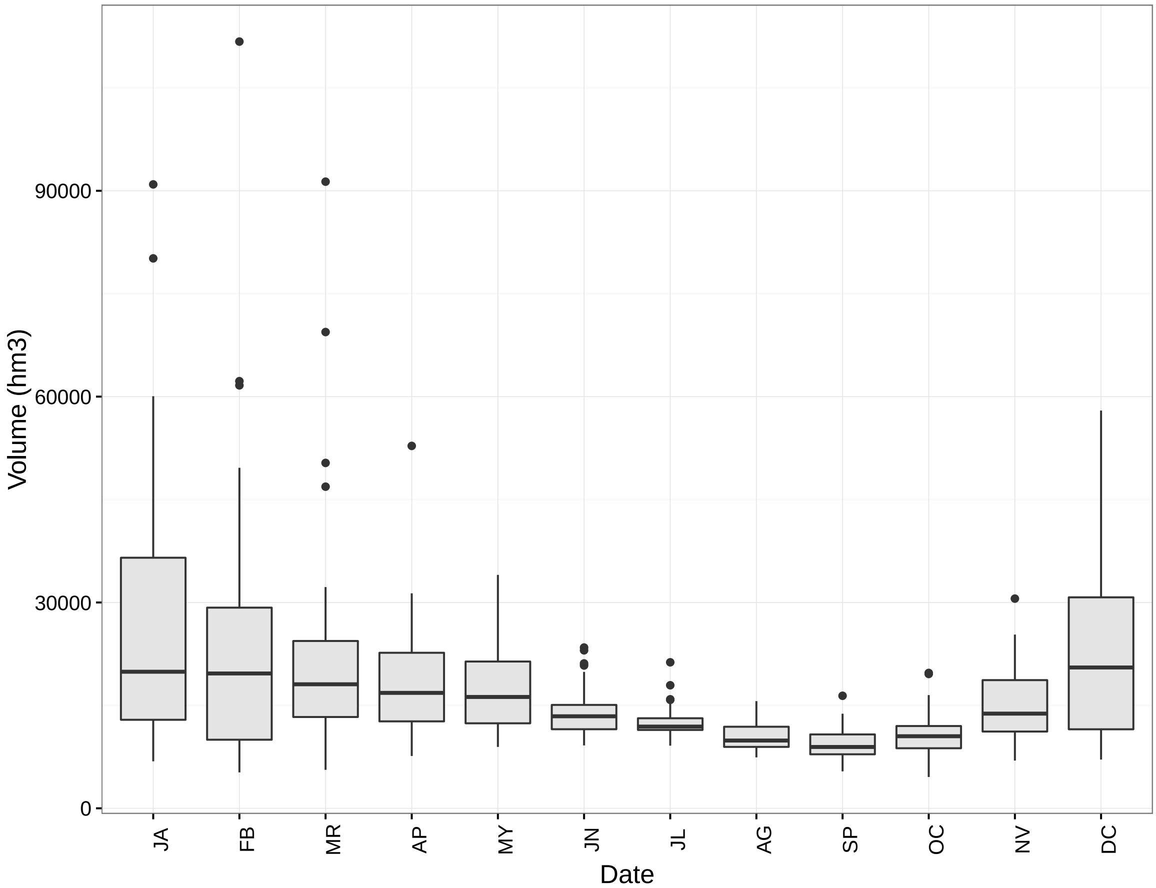

Figure 4.15: ROEA [23] reservoir outflows ($hm^3/month$) by basin boxplot

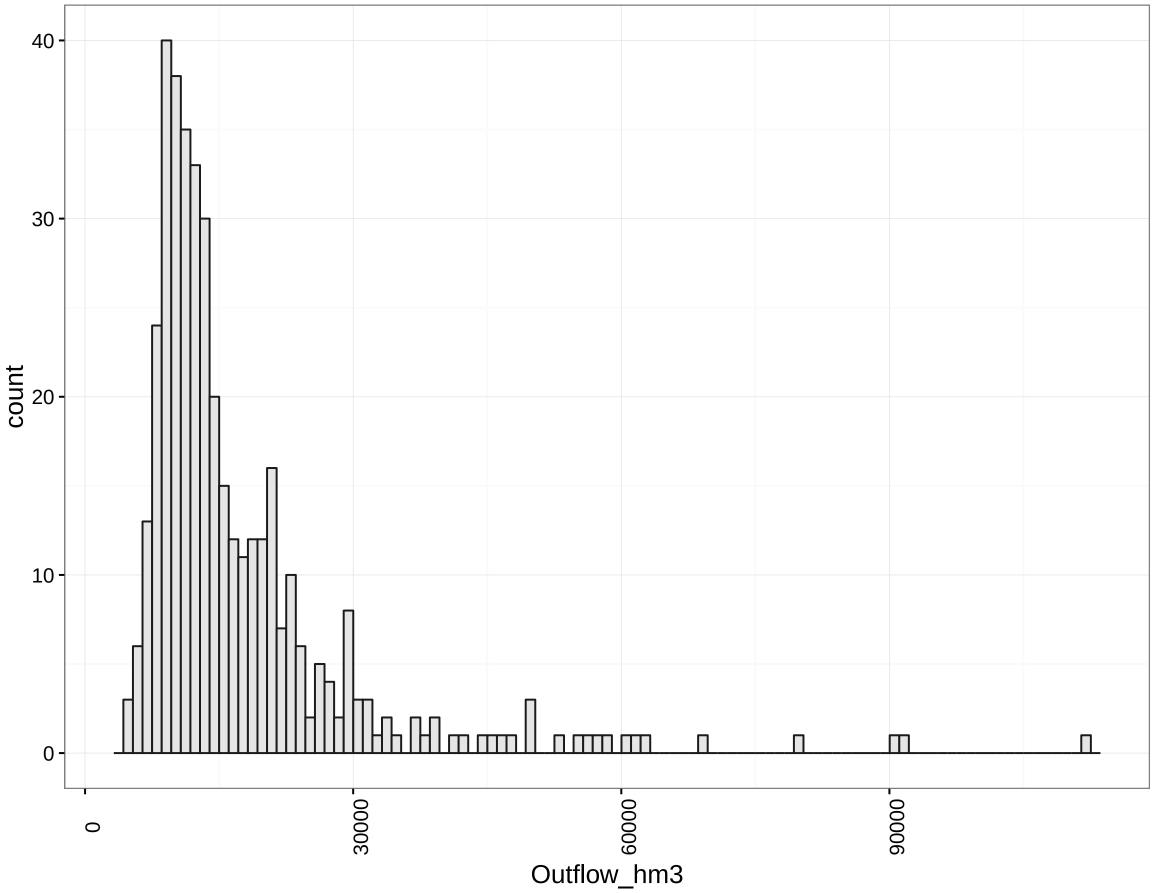

Figure 4.16: ROEA [23] reservoir outflows ($hm^3/month$) by basin histogram

4.5 Hydroenergy data

The Spanish electricty system operator Red Eléctrica de España (REE) [24] has aggregated data for Spain for the amount of hydroelectricty in GWh produced in every month from 1990 to 2015 as shown in Figure 4.17 and Figure 4.18. REE also has data for the producible hydroelectric energy in each month which is defined as the theoretical maximum energy producible after taking into account abstractions from users. The producible hydroenergy data is available at REE aggregated basins shown in Figure 4.19 as well as for Spain as a whole as shown in Figure 4.20. REE also provides data for hydroelectric reserves which is defined as the amount of energy that would be produced if all the water in the reservoirs was drained. A distinction is made between reservoirs which can be drained completely with a single year (annual) and those that would take more than a single year (hyper annual) and the historical data is shown in Figure 4.21 and Figure 4.22. Finally the hydroenergy in GWh produced, producible and reserves are compared together in Figure 4.23 and Figure 4.24. As expected when the hydroenergy produced is greater than the producible the reserves go decrease and vice-versa.

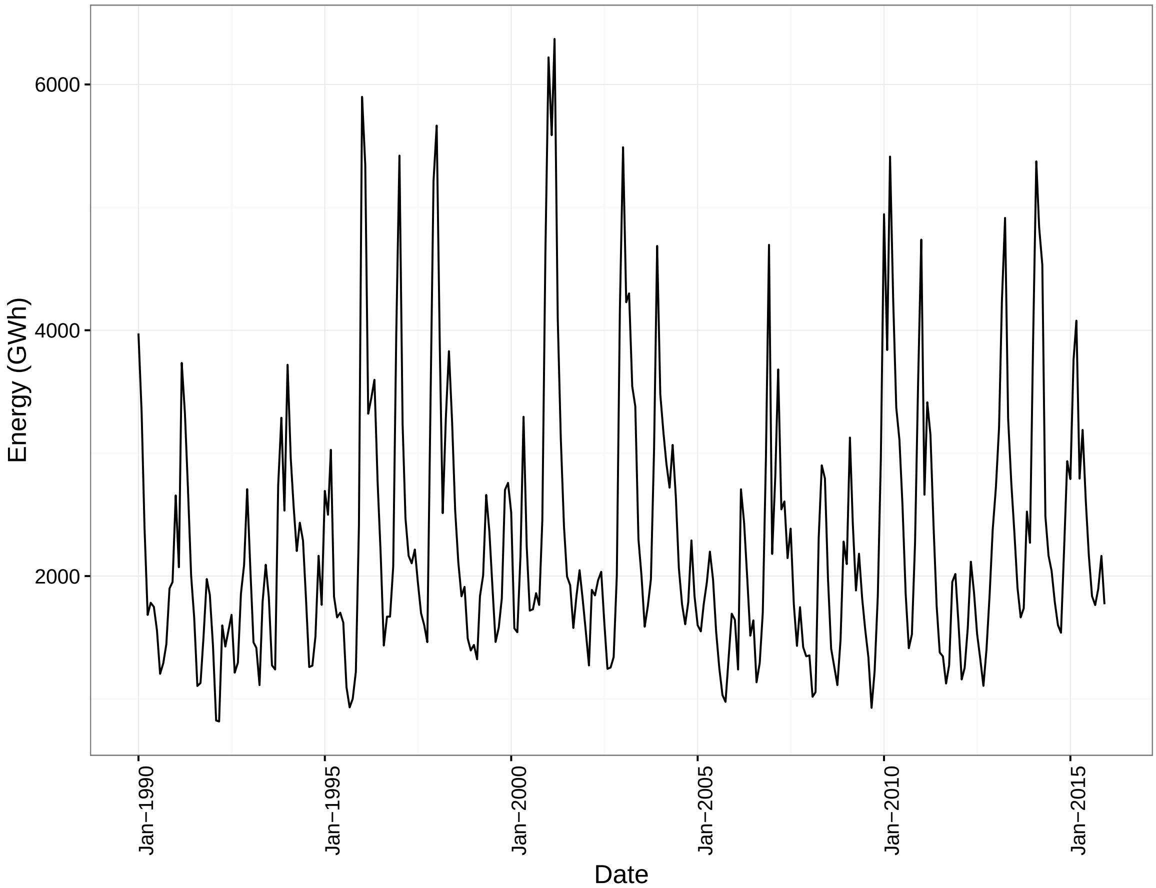

Figure 4.17: REE [24] hydroenergy produced ($GWh/month$) historical series

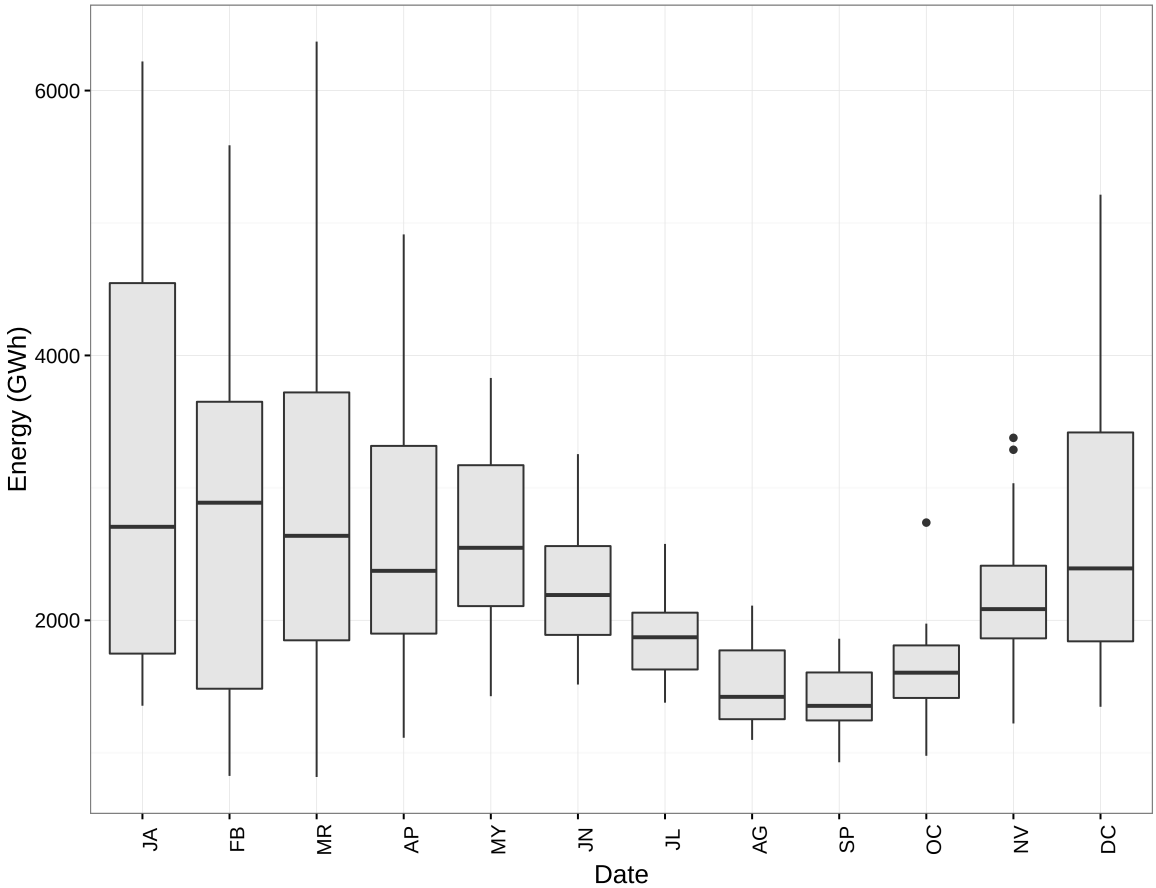

Figure 4.18: REE [24] hydroenergy produced ($GWh/month$) boxplot

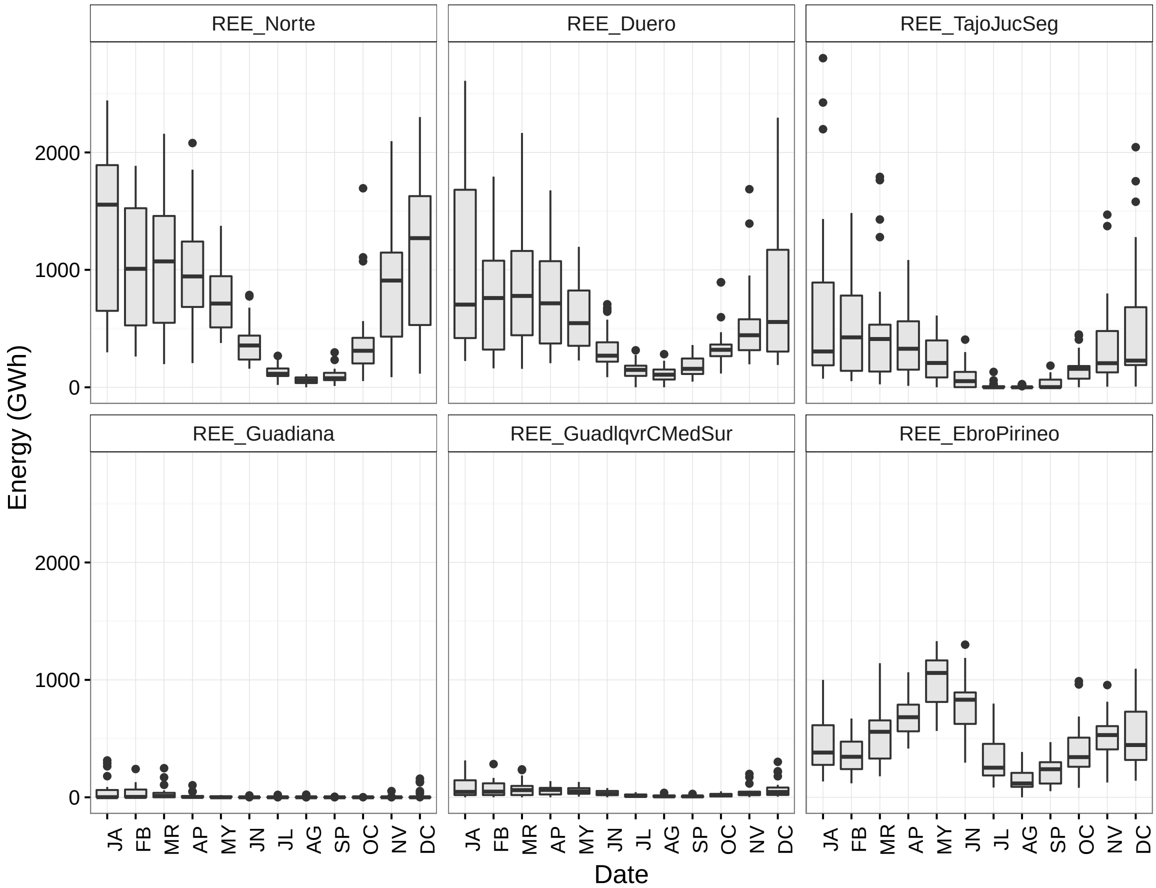

Figure 4.19: REE [24] producible hydroenergy ($GWh/month$) by aggregated basins boxplots

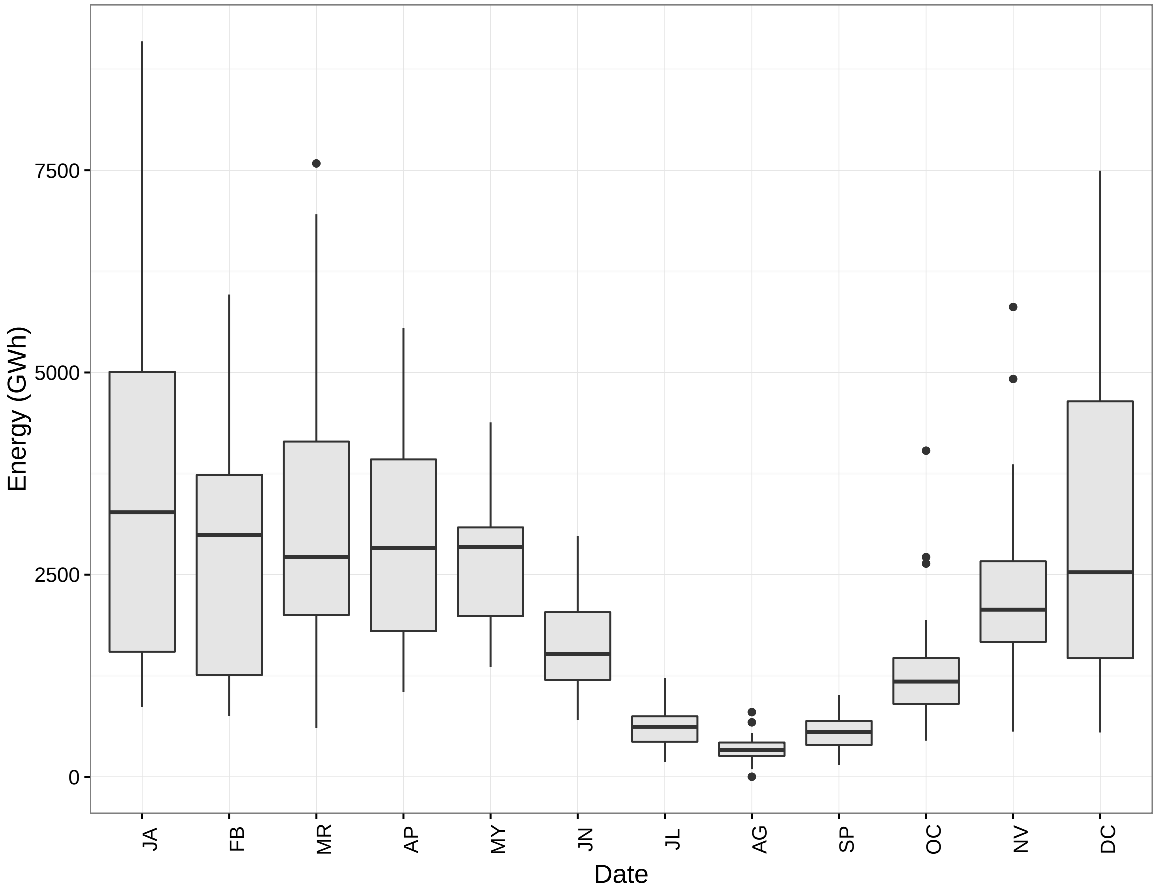

Figure 4.20: REE [24] producible hydroenergy ($GWh/month$) Spain boxplot

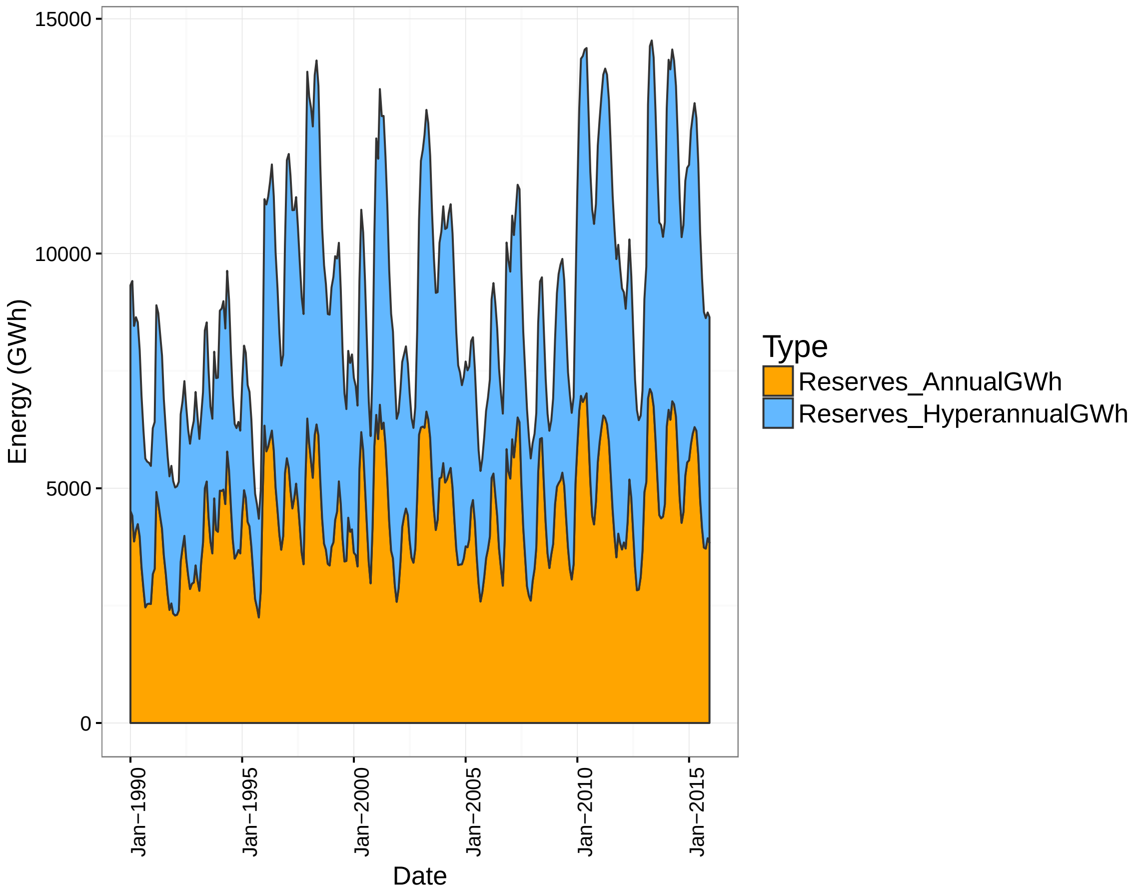

Figure 4.21: REE [24] annual and hyperannual hydroenergy reserves ($GWh/month$) historical series

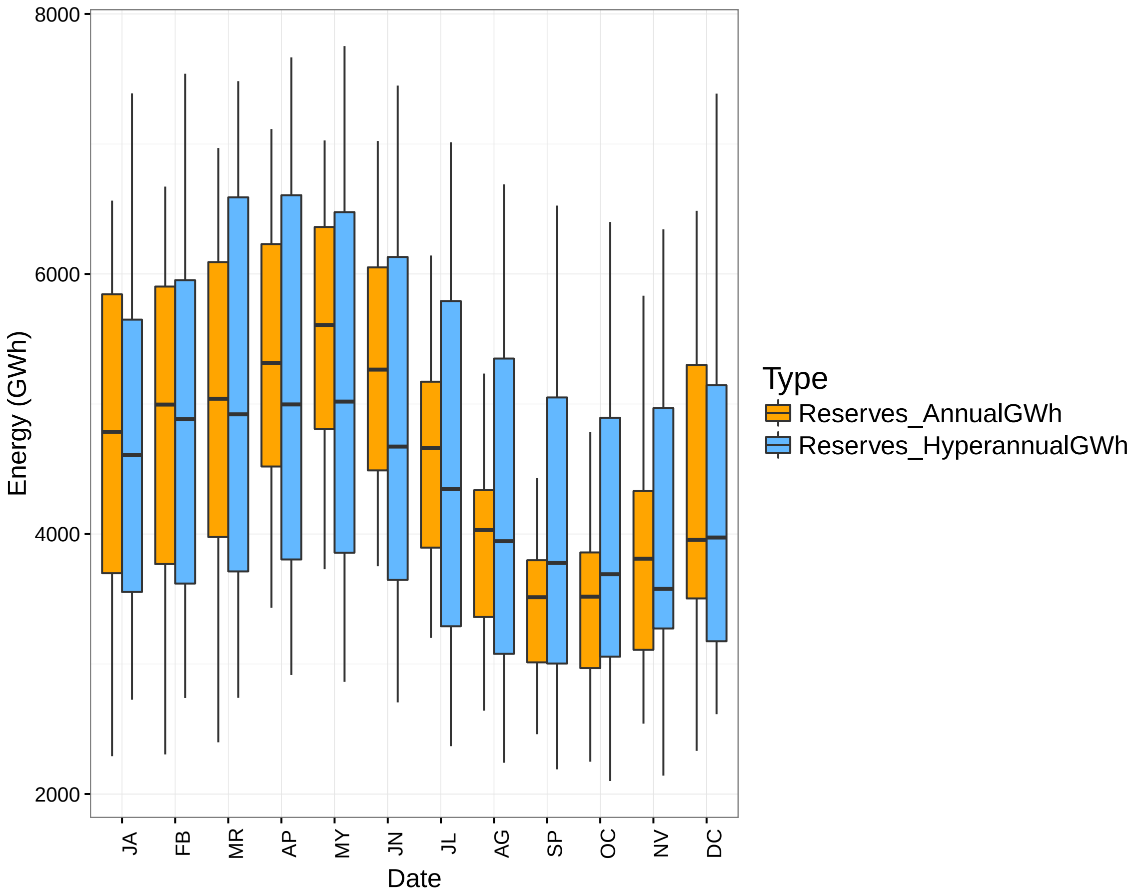

Figure 4.22: REE [24] annual and hyperannual hydroenergy reserves ($GWh/month$) boxplots

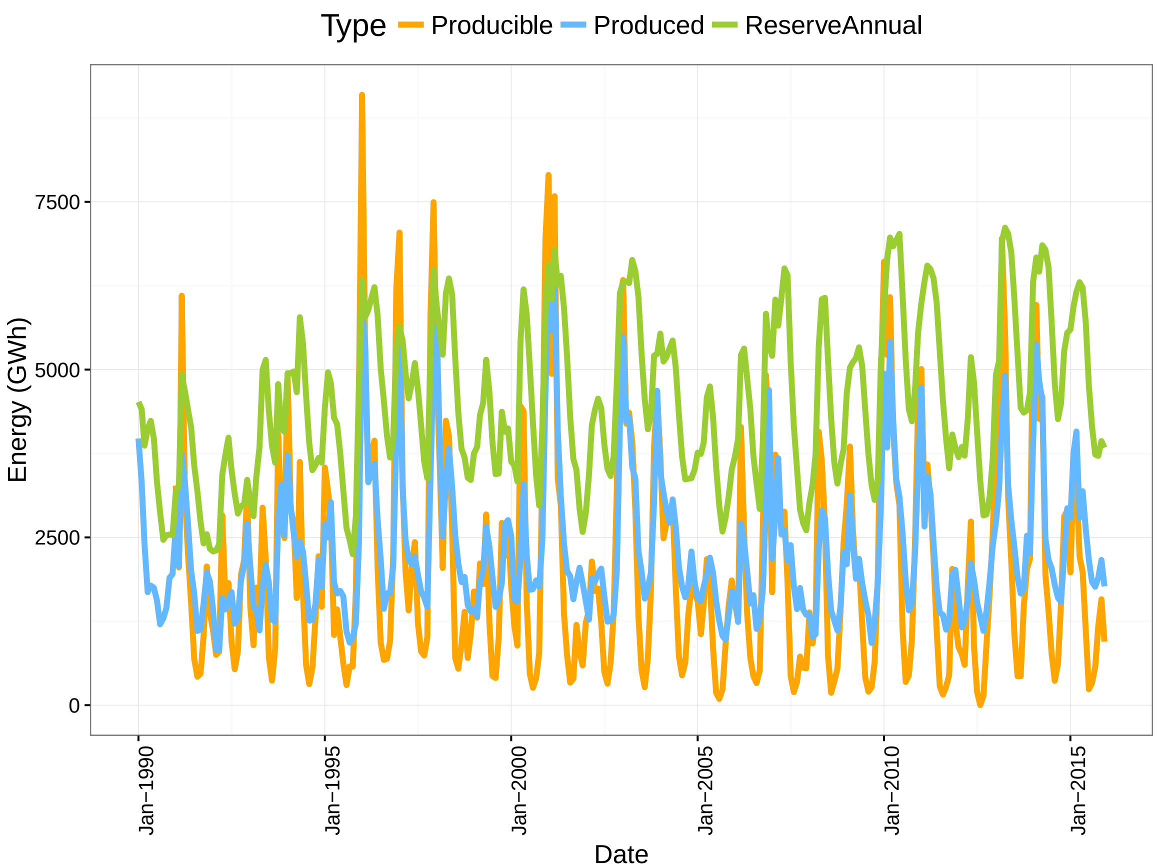

Figure 4.23: REE [24] hydroenergy produced, producible and reserves ($GWh/month$) historical series

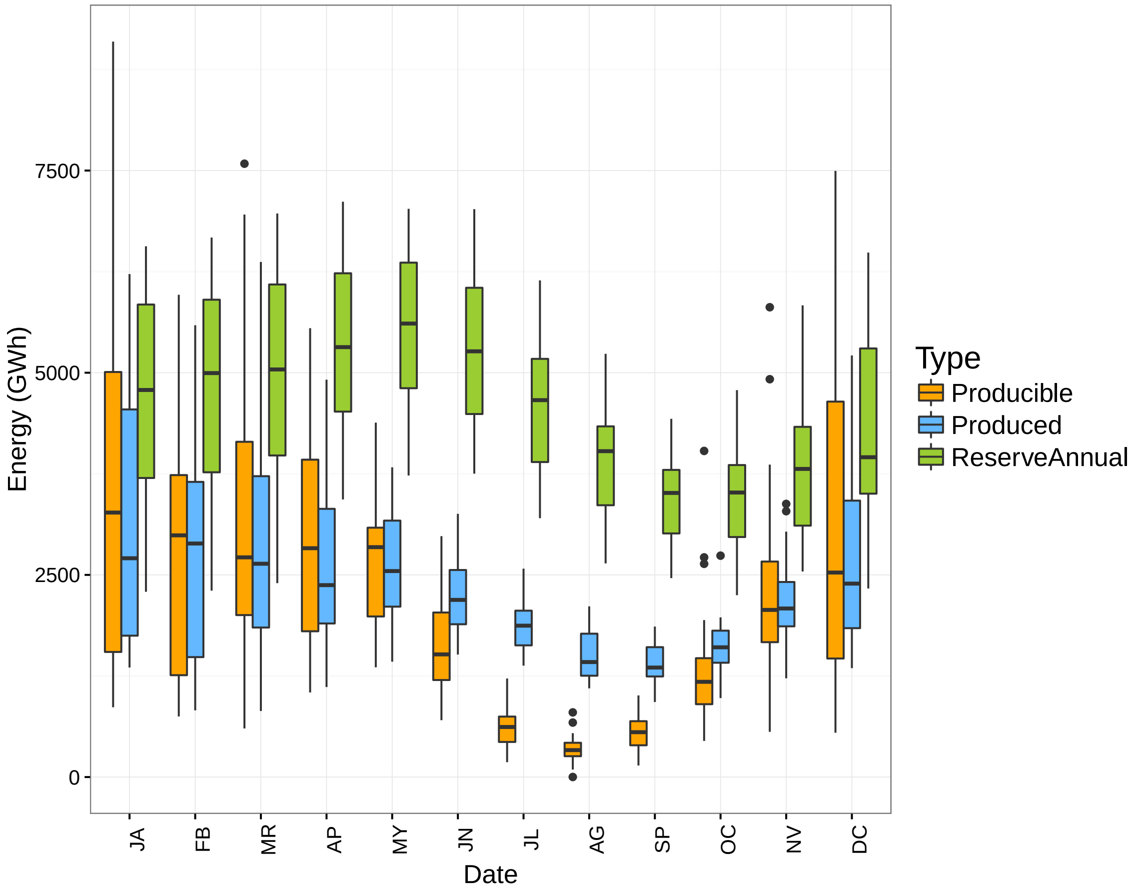

Figure 4.24: REE [24] hydroenergy produced, producible and reserves ($GWh/month$) boxplot

4.6 Hydroenergy-Outflow Relationship

The relationship between hydropower production and discharge from a reservoir can be formulated by equating it to the potential energy of water falling from a certain height as shown in Equation 4.6.1.

$$P = \eta \rho q g h \tag{4.6.1}$$

where P represents the output power ($Watt$), η is the is the overall efficiency of the hydro plant (i.e. the product of the efficiencies of the turbine and the generator), ρ is the water density (kg), q is the water flow (m^2/s), g is the acceleration of gravity (kg/m^3), and h is the net head (m). To convert this to energy we can multiply by the time period considered.

In order to incorporate this relationship into a linear model the equation is constructed in the form shown in Equation 4.6.2 where y represents the hydropower P, x the discharge q, m the slope and c the intercept.

$$y = mx + c \tag{4.6.2}$$

Comparing Equation 4.6.1 to Equation 4.6.2, we can see that the slope m can be expressed by the term $\eta \rho g h$ and the constant c is 0 meaning that when the discharge is 0 the output power is also 0. Now, for a linear relationship the term $\eta \rho g h$ is assumed to be constant meaning that the head h will be assumed to be fixed. This is a big assumption because the head clearly changes with the volume of water in a reservoir and this in turn effects the power production. This relationship and the impacts of using a constant head are explored below.

As a first step some simple linear regressions can be explored between the historical power output and the discharge. Figure 4.25 shows the aggregated discharge volume in $hm^3/month$ for Spain on the x axis versus the aggregated Spanish hydroelectricty production in $GWh/month$. It is clear that the relationship is non-linear. The dashed vertical line at about 29,000 hm^3 shows the outflows which are one standard deviation away from the mean monthly outflows. Three linear models, lm1, lm2 and lm3 are shown on the plot in red, blue and green respectively. Each linear model is defined by a y-intercept and a slope relating outflow during a certain month to the hydroenergy produced. lm1 accounts for all the data and has no intercept restriction. Since a y-intercept greater than 0 is not possible (0 outflow should equal 0 energy production) lm2 considers all the data but forces the model intercept to 0. Finally, lm3 forces the model through the origin and only considers a subset of the data, with outflows less than 1 SD away from the mean. It is clear than lm2 and lm3 will overestimate energy production for large outflows. This is one of the drawbacks of assuming a constant head.

Next, power output from discharge is explored by analyzing several possible representative reservoir shapes in order to estimate an average head per river basin and then using Equation 4.6.1 to calculate the power output. The head or depth of a reservoir can be related to the volume of the reservoir using a power function of the form shown in Equation 4.6.3, in which V is the volume, D is the depth or head and k and α are coefficients defing the curvature and slopes of the reservoir shape. A similar relationship can be formed for the Volume and surface area. These relationships are detailed in Grin 2014 [25] and an adaption from the study is shown in Figure 4.26.

$$V = kD^{\alpha} \tag{4.6.3}$$

As seen in the figure α determines the concavity or convexity of the reservoir while k determines the slope of the sides. In the study, for the depth volume relationship, k was found ot have a large range varying from basin to basin. In the Madalena basin in Brazil k was found to vary between 2820 to 6800. In the region of Ceará k varied from 30 to 28,274, with a mean of 2,432. The α coefficient defining the concvexity had a smaller range and in the Madalena Basin varied between 2.62 and 2.83 while in Ceará the values varied between 2.16 and 5.21 with an average value of 3.11. A set of coefficients with α equal to 2,3 and 4 and k equal to 30,2500 and 10000 are used to explore different shapes. These coefficients are used together with the average reservoir volume levels from Table 4.2 to get the corresponding average head in each basin. Figure 4.27 shows how the heads calculated using the different coefficients vary by coefficient and volume, while Figure 4.28 shows how the head varies by coefficient and basin. These mean heads are then used in Equation 4.6.1 to estimate the hydropower production from historical discharges. Six models are tested with α values varying from 2,3 and 4 and k values of either 2500 and 10000. k of 30 represented almost vertical slopes leading to extremely high heads and lead to overestimated power outputs which did not correspond well with the historical data and is therefore not shown in the figures.

Thus in total nine models were considered. The first three: lm1, lm2 and lm3 represent the linear regression models while the next six: lm4 to lm6 represent the linear models developed based on Equation 4.6.1 and Equation 4.6.3 exploring different reservoirs shapes and volume-head-power relationships. A summary of the models and their details is provided in Table 4.6. Table 4.7 details the relationships for each basin for models, lm4 to lm9.

Next the models are used to predict values of hydroenergy based on the historical outflow values. The model fitted values are plotted against the actual hydroenergy production in Figure 4.29 and Figure 4.30. The residuals of the model fitted values and the actual values are shown in Figure 4.31, Figure 4.32 and Figure 4.33.

From the results we see that the best fitting model is lm1 which has residuals with a mean of 0. However, this model uses a y intercept which would not make sense in reality allowing power production from 0 outflows. This model is thus discarded. The next best models are lm3, which uses a linear regression considering only small outflow values, and lm8 which considers an α value of 3 and k of 10000. Both these models show good results for small outflows, but overestimate the output for large outflows. This is expected because a constant head is used. However, as seen in Figure 4.33 the overestimation occurs for only a small subset of the outflows which occur 2 standard deviations away from the mean outflow. For outflow values less than one standard deviation from the mean both models show good results.

Table 4.6: Summary of linear models used to estimate hydropower production from outflows

Model	Description	Data Used	α	k	Relationship y= Hydroenergy x= Outflow
lm1	Linear regression model	All Outflows, Hydroenergy	-	-	y = 0.078x + 1001
lm2	Linear regression model	All Outflows, Hydroenergy	-	-	y = 0.1167x
lm3	Linear regression model	< 1 SD from mean Outflows	-	-	y = 0.1514x
lm4	$P = \eta\rho qgh$ $V = kD^{\alpha}$	Mean Volume	2	2500	See Table 4.7
lm5	$P = \eta\rho qgh$ $V = kD^{\alpha}$	Mean Volume	3	2500	See Table 4.7
lm6	$P = \eta\rho qgh$ $V = kD^{\alpha}$	Mean Volume	4	2500	See Table 4.7
lm7	$P = \eta\rho qgh$ $V = kD^{\alpha}$	Mean Volume	2	10000	See Table 4.7
lm8	$P = \eta\rho qgh$ $V = kD^{\alpha}$	Mean Volume	3	10000	See Table 4.7
lm9	$P = \eta\rho qgh$ $V = kD^{\alpha}$	Mean Volume	4	10000	See Table 4.7

Table 4.7: Summary of linear models used to estimate hydropower production (y) from outflows (x). Models lm4 to lm9.

Basin	Average Volume (hm3)	a=2 k=2500	a=3 k=2500	a=4 k=2500	a=2 k=10000	a=3 k=10000	a=4 k=10000
GalCosta	360.01	y = 0.06x	y = 0.08x	y = 0.09x	y = 0.03x	y = 0.05x	y = 0.07x
MinoSil	1,128.02	y = 0.1x	y = 0.11x	y = 0.12x	y = 0.05x	y = 0.07x	y = 0.09x
CantbrOc	382.7	y = 0.06x	y = 0.08x	y = 0.09x	y = 0.03x	y = 0.05x	y = 0.07x
CantbrOr	45.51	y = 0.02x	y = 0.04x	y = 0.06x	y = 0.01x	y = 0.03x	y = 0.04x
Duero	4,591.2	y = 0.18x	y = 0.16x	y = 0.16x	y = 0.1x	y = 0.11x	y = 0.12x
Tajo	6,117.41	y = 0.2x	y = 0.18x	y = 0.17x	y = 0.11x	y = 0.12x	y = 0.12x
Guadiana	4,715.96	y = 0.18x	y = 0.16x	y = 0.16x	y = 0.1x	y = 0.11x	y = 0.12x
TintOdPdra	94.01	y = 0.03x	y = 0.05x	y = 0.07x	y = 0.02x	y = 0.04x	y = 0.05x
Guadalquivir	3,939.96	y = 0.17x	y = 0.16x	y = 0.15x	y = 0.09x	y = 0.1x	y = 0.11x
GuadBarbte	737.97	y = 0.08x	y = 0.1x	y = 0.11x	y = 0.05x	y = 0.07x	y = 0.08x
CMedAndlz	319.76	y = 0.06x	y = 0.08x	y = 0.09x	y = 0.03x	y = 0.05x	y = 0.07x
Segura	664.84	y = 0.08x	y = 0.09x	y = 0.1x	y = 0.04x	y = 0.06x	y = 0.08x
Jucar	1,536.05	y = 0.11x	y = 0.12x	y = 0.12x	y = 0.06x	y = 0.08x	y = 0.09x
Ebro	3,584.64	y = 0.16x	y = 0.15x	y = 0.15x	y = 0.09x	y = 0.1x	y = 0.11x
CICat	218.29	y = 0.05x	y = 0.07x	y = 0.08x	y = 0.03x	y = 0.05x	y = 0.06x

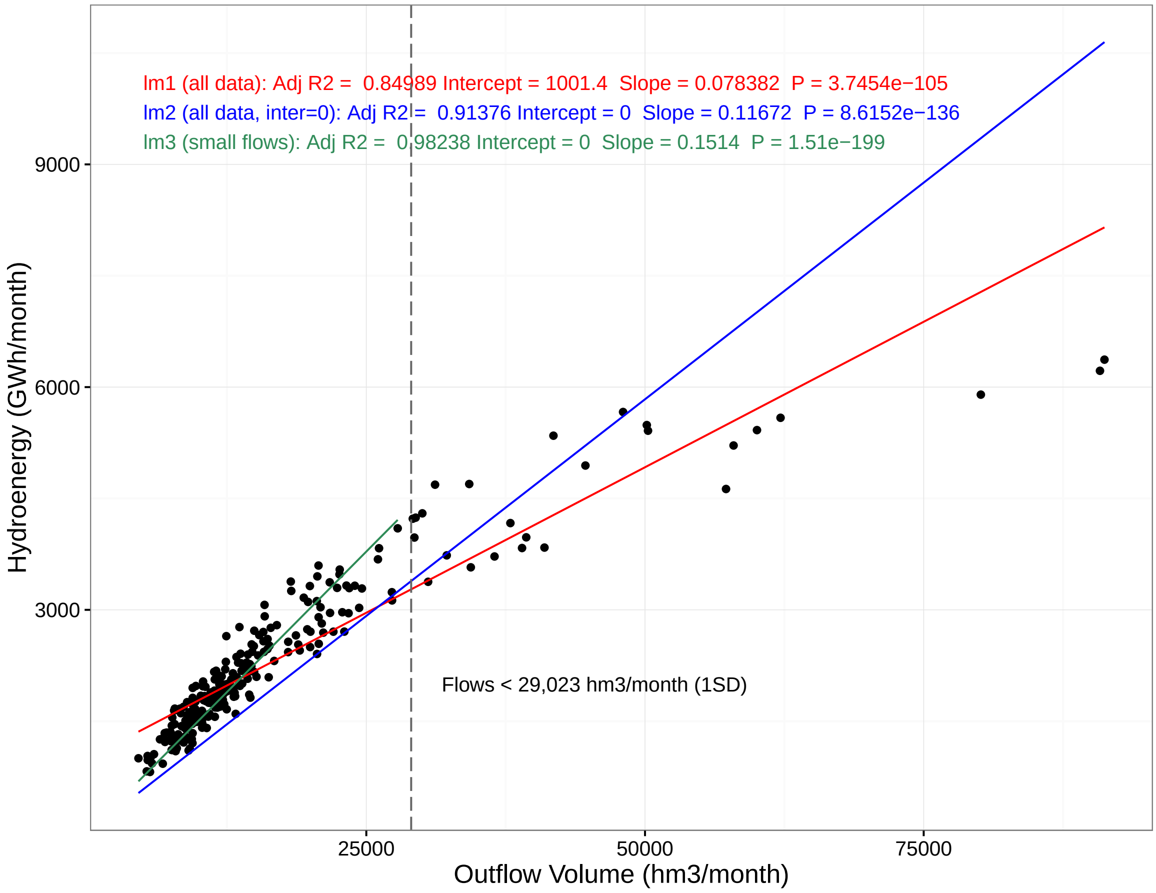

Figure 4.25: Linear models from REE [24] hydroenergy ($GWh/month$) versus ROEA [23] Outflow ($hm^3/month$) data

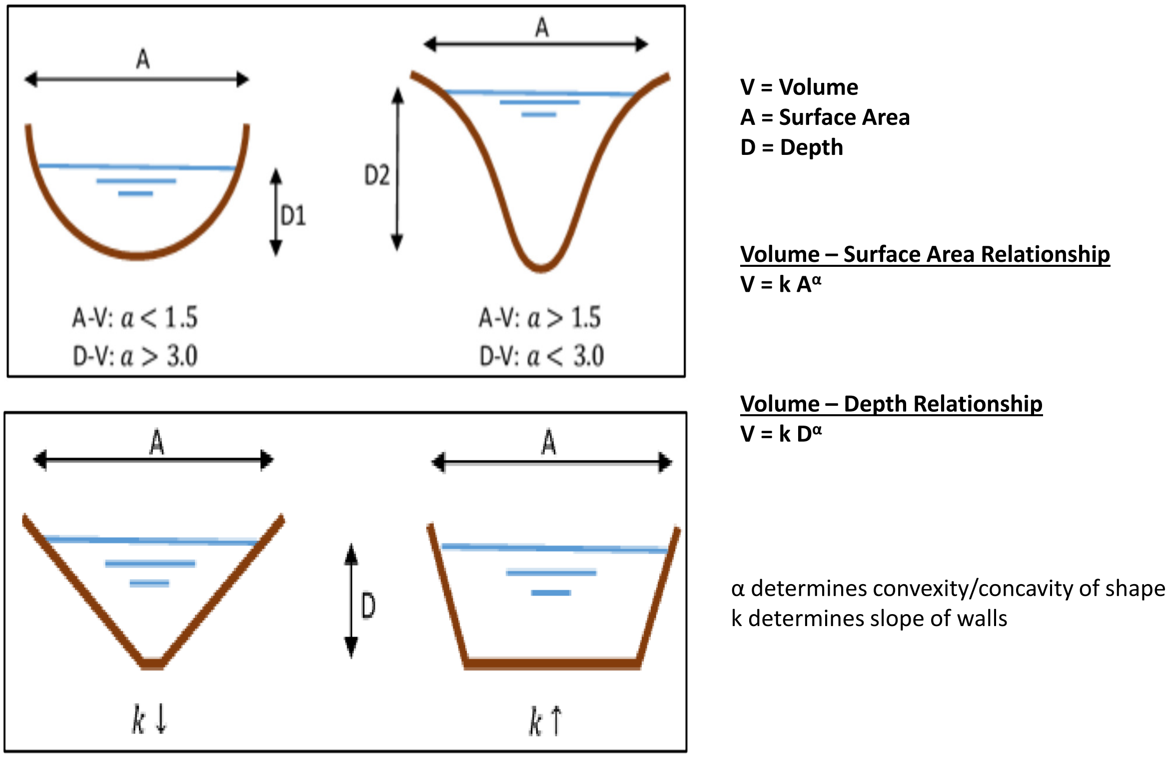

Figure 4.26: Reservoir shape assumptions for head calculations. Adapted from Grin 2014 [25]

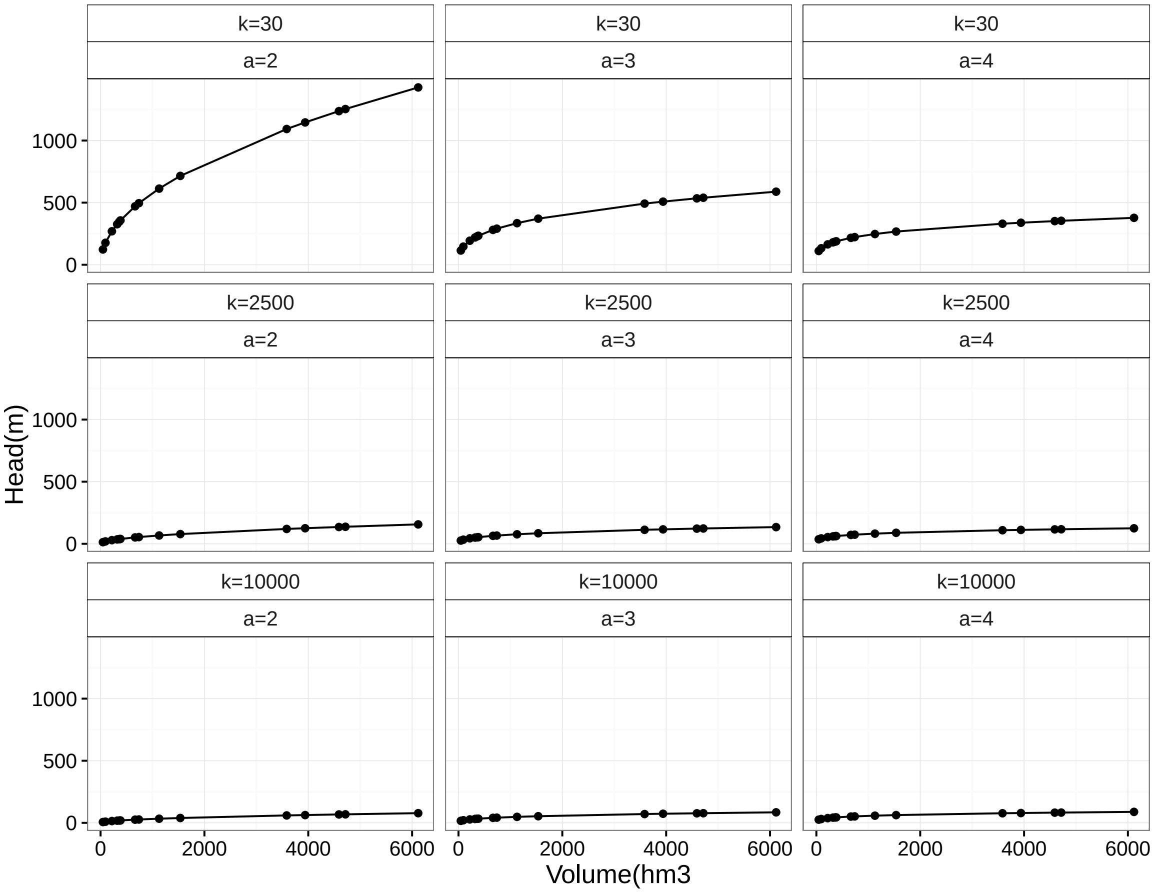

Figure 4.27: Variation of reservoir heads by volume and reservoir shape assumption

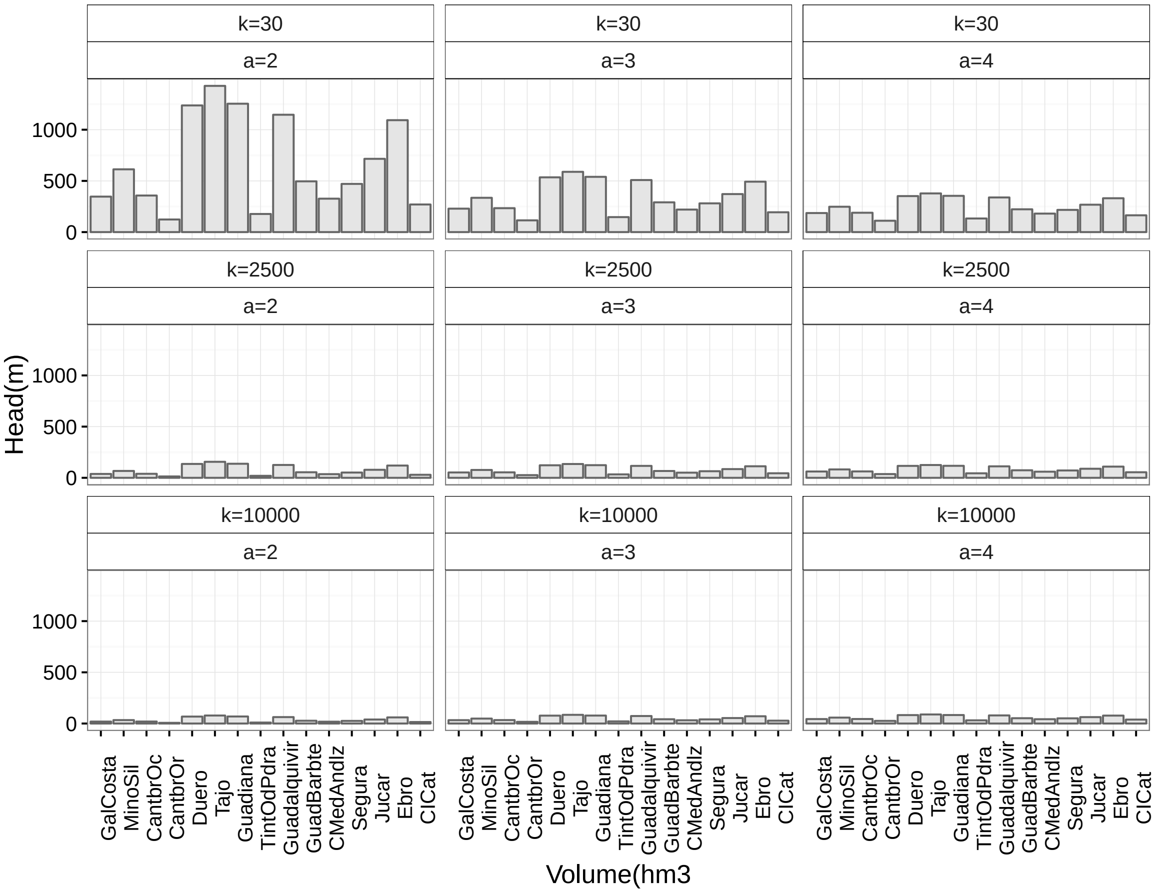

Figure 4.28: Variation of reservoir heads by basin and reservoir shape assumption

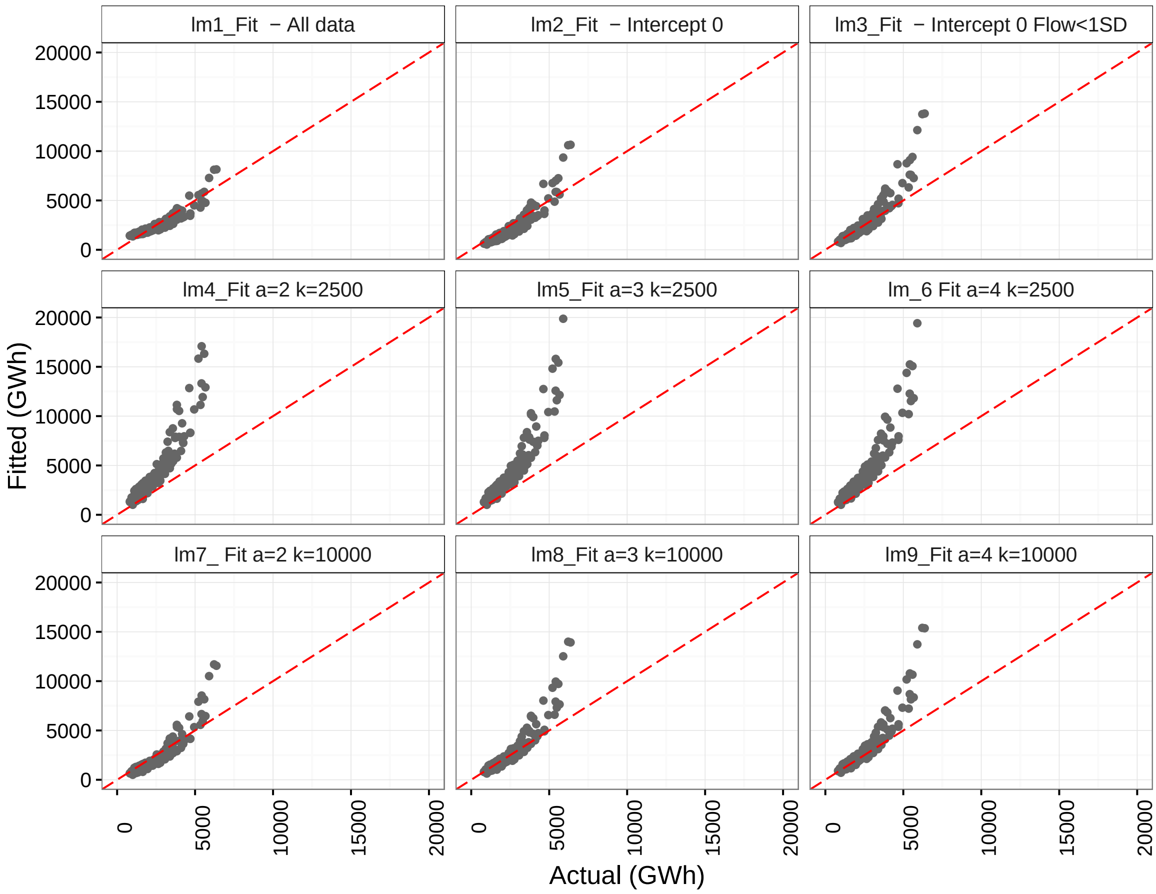

Figure 4.29: Model fitted values based on ROEA [23] Outflow ($hm^3/month$) data versus actual REE [24] hydroenergy ($GWh/month$) data

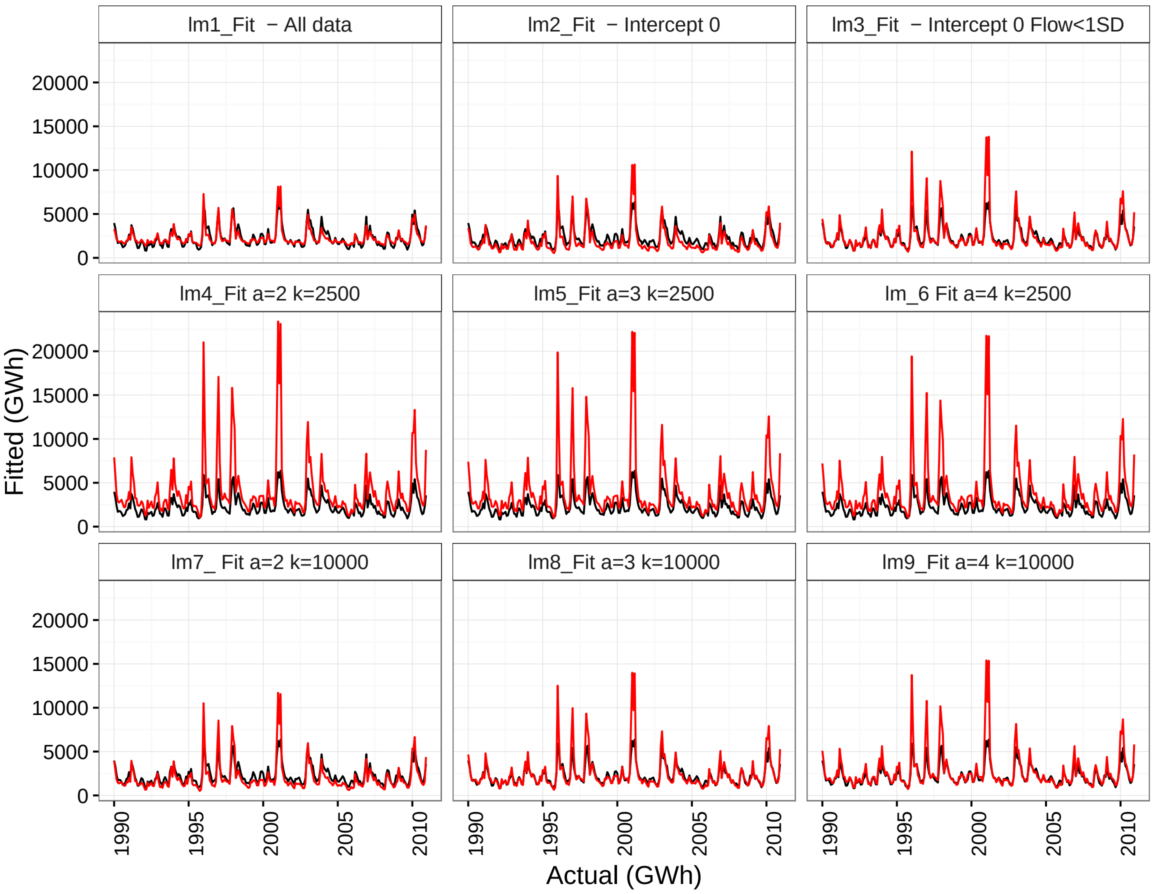

Figure 4.30: Model fitted values based on ROEA [23] Outflow ($hm^3/month$) data versus actual REE [24] hydroenergy ($GWh/month$) data historical series

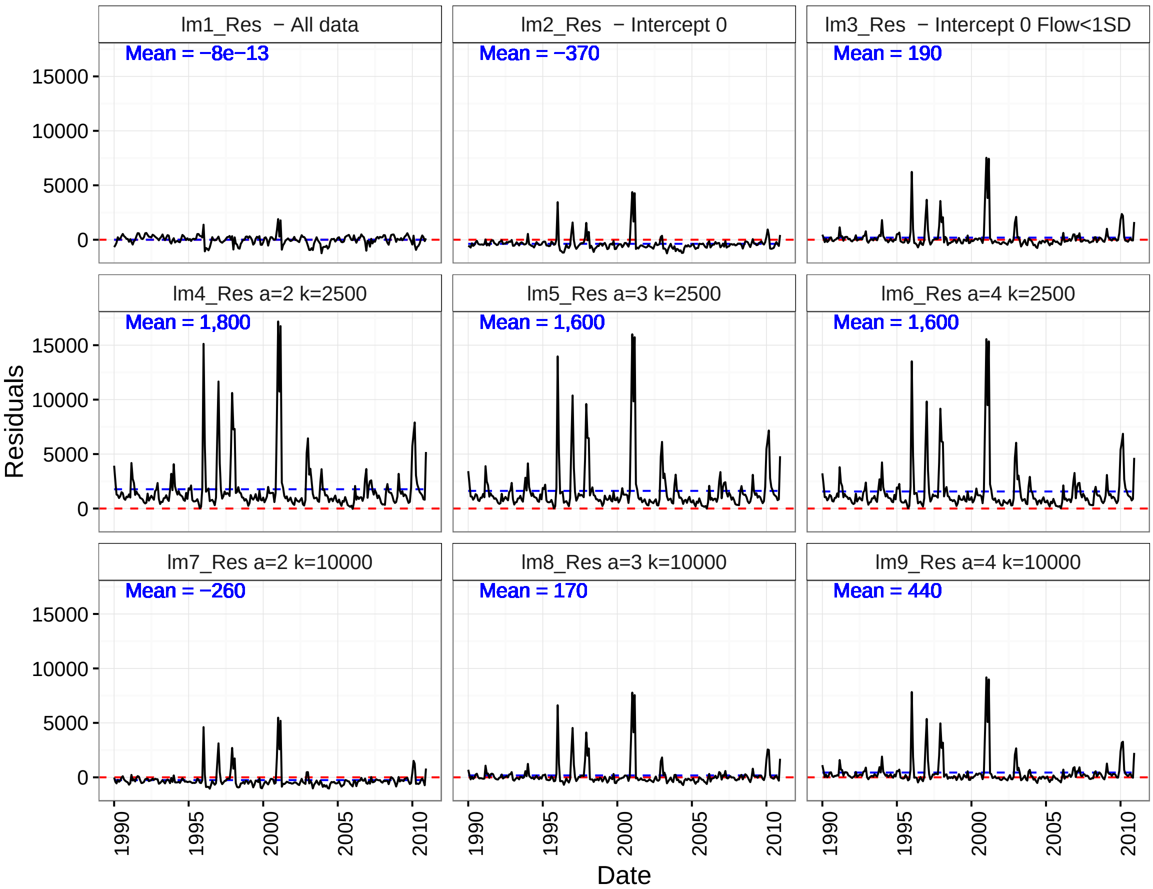

Figure 4.31: Model residuals from the difference between fitted values based on ROEA [23] Outflow ($hm^3/month$) data and actual REE [24] hydroenergy ($GWh/month$)

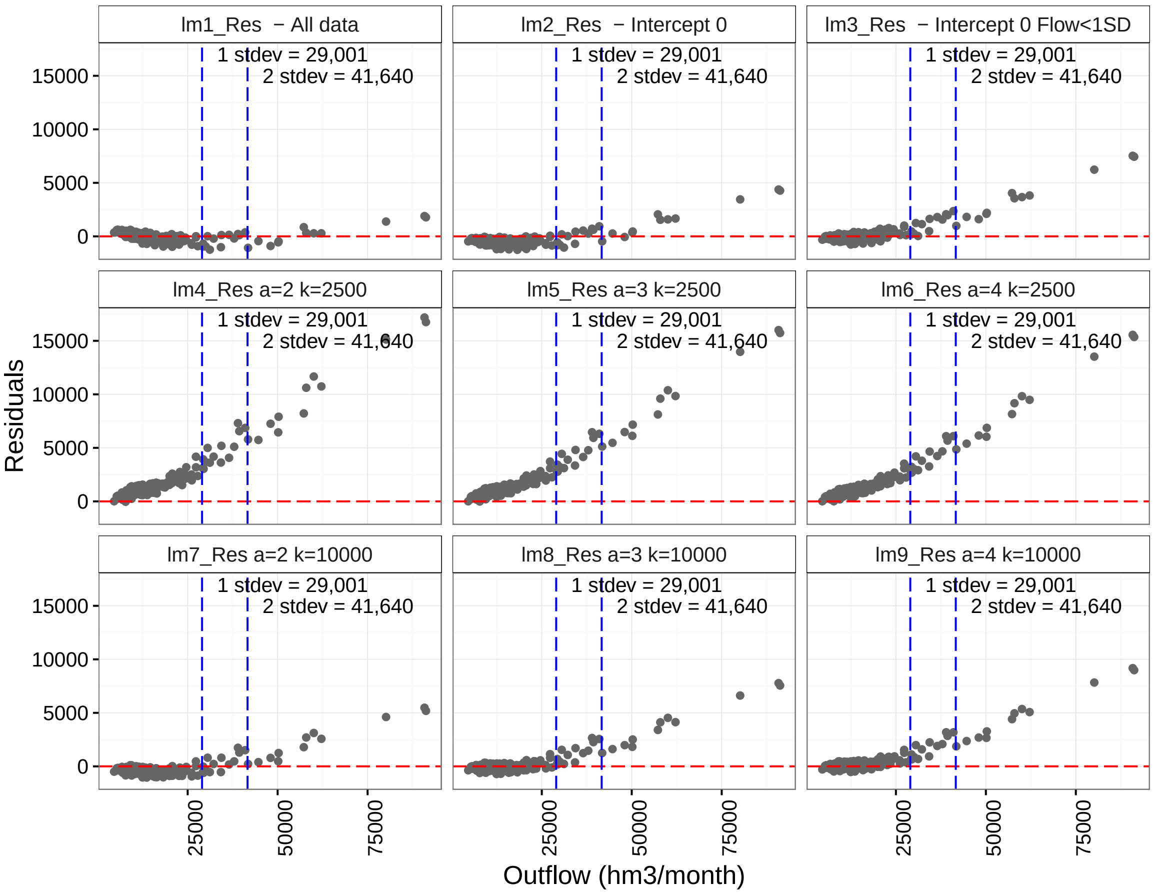

Figure 4.32: Model residuals from fitted values based on ROEA [23] Outflow ($hm^3/month$) data versus actual REE [24] hydroenergy ($GWh/month$)

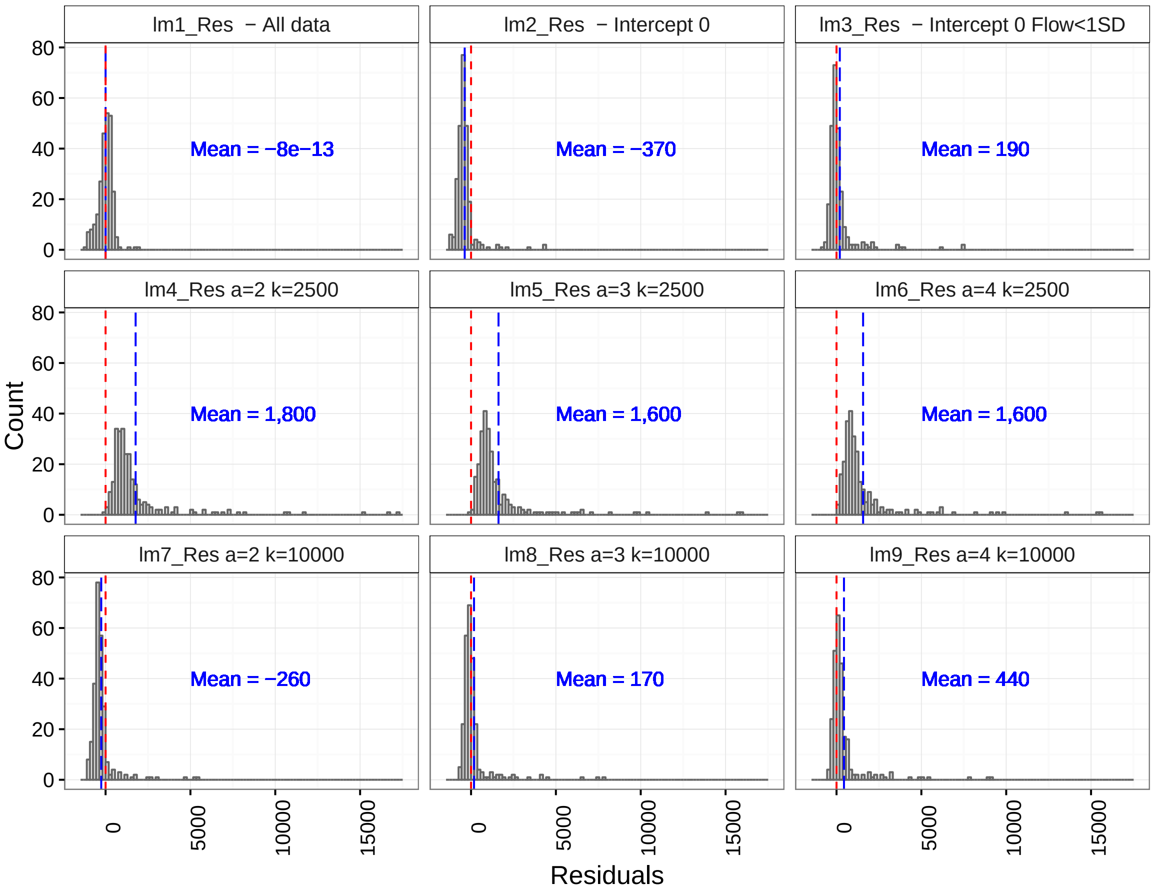

Figure 4.33: Model residuals from fitted values based on ROEA [23] Outflow ($hm^3/month$) data versus actual REE [24] hydroenergy ($GWh/month$) histograms

4.7 Parameter Summary

4.8 Worked Example

4.9 Costs

4.10 Energy Consumption

4.11 Water Efficiency

4.12 Existing Capacity

4.13 Storage

4.14 Future Predictions and Climate Change

Chapter 5

Groundwater Pumping

5.1 Introduction

In this section we discuss groundwater resources and pumping in Spain and the inputs used in the model. Several different studies [26, 27, 28, 29, 30, 31, 2] were used to calculate the different groundwater parameters used in the model. The parameters are summarized in Table 5.1.

[27] Spain is the most arid country in European Union. Groundwater use in Spain has grown from $2,000 hm^3/yr$ in 1960 to more than $6,500 hm^3/yr$ in 2006. On average groundwater provides 15 to 20% of all water used in the country with some isalnds and areas receiving 100%. Over 12 million people (one-third of total population) depend on groundwater for agriculture, industrial and drinking purposes. Traditionally only sedimentary, carbonated or volcanic formations with high permeability considered aquifers and accounted for 180,000 km^2 (1/3 surface area of Spain). The 1985 Water act identified 411 hydrological units. Then the Water Framework Directive introduced the concept of water bodies as subunits of river basins. Water bodies defined as those serving more than 50 people with drinking water or supply over 10m3/day. Under this new classification 699 groundwater bodies have been identified covering 350,000 km^2 (70% of Spain surface area). Sizes vary from $2.5 km^2$ Gernika (Pais Vasco basin) to $20,000 km^2$ Elsa-Valderaduey (Duero). Average size is about 500 km^2. Total volume from different estimates between $150,000 Mm^3$ to $300,000 Mm^3$ (only acount for 100-200m depth and do not account for unofficial hydrogeological units). Spain reservoirs provide about $53,000 Mm^3$ of which on average $37,425 Mm^3$ are annually available. Renewable groundwater sources are estimated to be about $30,000 Mm^3$.

[30] In Denmark, Malta, Saudi Arabia, among other countries, it is the only source of water supply. In other countries, it is the most important part of the entire water resources, like in

Tunisia, where it is 95 % of total water resources, in Belgium it is 83 %, in the Netherlands, Germany and Morocco it is 75 %, and in most European countries (Austria, Belgium, Denmark, Hungary, Romania and Switzerland) groundwater use exceeds 70 % of the total water consumption (Zektser and Everett 2004). The world average groundwater provides 42.7 % of the consumptive use for irrigation, and 37.5 % of the irrigated area is equipped for irrigation with groundwater. In Spain, groundwater provides 20 % of the total irrigation water, and 28 % of the irrigation area, which gives rise to 38 % of the total agronomic production.

[1] A study from Australia [1] discusses the two main types of groundwater pumps, bores and spearpoints. Spearpoints are system of groundwater pumps used mainly for shallow salinity and waterlogging control, while bores are used for both shallow and deep water extraction to supplement surface water resources. In the study a distinction is made between shallow bores used to reach the Shepparton layer aquifer (Australia) (10 to 30 meteres) and deep bores used to reach aquifers in the Calivil and Renmark layers (approximately 150 to 300 m). Shallow boreholes also have low yields ($< than 10 ML/day$) while deep boreholes usually have a higher yield (up to $30 ML/day$).

[28, 29] Current groundwater abstraction volume in Spain is around $7 km^3/year$ and the recharge volume is about $30 km^3/year$. Dsicusses in detail the policies governing groundwater management and the complexities in planning for the future.

Current usage of groundwater resources in different sectors is estimated in Table 10.1 [27].

5.2 Parameter Summary

Based on the studies in this chapter we assume that on average new groundwater wells will be bore type wells with submerged turbine pumps. All new wells will extend to atleast depth 10m below the existing groundwater level. Discharge level will be assumed to be at ground surface thus giving a pumping head equal to the groundwater level at the time. If the existing capacity in L/s is not sufficient to meet the demands, new boreholes will be installed to supplement the demand. The parameters to be used are shown in Table 5.1, Table 5.2 .

Table 5.1: Groundwater parameters used in model

Parameter	Name in Model	Value
Lifetime (years)	s_life_gwpump	30
Amortization rate (%)	s_intrate_gwpump	4
Depth gelow GW level (m)	s_depthblwgwtable_gwpump	10

Table 5.1: Groundwater parameters used in model

Parameter	Name in Model	Value
Pumping efficiency (%)	s_pumpEff_gwpump	0.8
Derating efficiency (%)	s_deratingEff_gwpump	0.75
Cost OnM (€/hm^3)	s_cost_gwpump_OnM	3,913
Cost Inv (€/((hm^3/mnth)/m))	s_cost_gwpump_Inv	5,530

Investment costs are calculated as an annuity and the parameter above (5,530) is multiplied by the water needed per month ($hm^3/month$) as well as the pumping head required (m) (groundwater level + the depth of pump below the level) to get the principal amount. The principal amount is then converted into an annuity based on the life time and amortization rate using the amortization formula Equation 5.2.1:

$$Annuity = Principal \times (i + i/((1+i)^n - 1)) \quad (5.2.1)$$

The energy consumed by groundwater pumping is calculated using Equation 5.5.1 [1] and multiplying the power calculated by hours run. Another option is also Equation 5.5.2 [2] for checking the values. The equations are repeated here and developed in more detail in the section on energy. The parameter in the model is:

s_nrg_gwpump (GWh)

$$P = (R \times H)/(102 \times E_p \times E_d) \quad \text{(5.5.1 repeated below)}$$

$$E = \phi \times W \times h \quad \text{(5.5.2 repeated below..)}$$

Initial groundwater levels are taken for the latest values available for averaged river basin water levels as discussed later. Groundwater pumping by basins is also summarized. Groundwater recharge is given as a percentage of the rainfall less the Evapotranspiration falling on different basins. The results are summarized in Table 5.2:

Table 5.2: Groundwater Parameters by River Basins

Basin	p_gwlevel_init_m(b) (m)	p_cap_gwPump_init_m(b)($hm^3/month$)	p_gwRchrg_prcn
Gal_Costa	4.5	0	0.18

Table 5.2: Groundwater Parameters by River Basins

Basin	p_gwlevel_init_m(b) (m)	p_cap_gwPump_init_m(b)($hm^3/month$)	p_gwRchrg_prcn
Mino_Sil	4.5	0	0.37
Cantbr_Oc	18	1.58	0.17
Cantbr_Or	9.7	2.75	0.22
Duero	26.4	30.92	0.22
Tajo	47.4	13.67	0.16
Guadiana	23.8	61.5	0.06
Tint_Od_Pdra	5.4	6.33	0.25
Guadalquivir	72.7	38.28	0.03
Guad_Barbte	16	3.97	0.29
C_Med_Andlz	83	35	0.73
Segura	99	39.83	0.73
Jucar	69.6	118.75	0.26
Ebro	52.2	16.5	0.33
CICat	34	35.33	0.18

5.3 Worked Example

Assume:

- Basin X has a capacity of 1000 L/s installed
- Water needed is in the month is 6,000,000,000 L
- Groundwater depth is 50m
- Liftime is 30 years, interest rate is 4%

Using the values from the parameter table we can calculate costs, energy and losses as follows:

- Water provided by current capacity = 1000 $L/s \times 60 \times 60 \times 24 \times 30 = 3,000,000,000$ $L/month = 3\ hm^3/month$
- Additional capacity needed is = $6,000,000,000 - 3,000,000,000\ L/month = 3,000,000,000$ $L/month = 1000\ L/s = 2.6\ hm^3/month$

- Investment cost (€) = $5529e/(hm^3/month)/m \times 2.6hm^3/month \times 50(m) = 716,548$ €
- Annuity (€) = $P(i + i/((1+i)^n - 1)) = 716,548 \times (0.04 + 0.04/(1.04)^{30} - 1) = 41,438$ €
- OnM costs (€) = 3,913 €$/(hm3) \times 6(hm^3)$ = 23,478 €
- Power needed $(kW) = 2315(L/s) \times 50(m)/(102 \times 0.8 \times 0.8) = 1891(kW)$
- Energy needed (GWh):
  - Using Equation 5.5.1 [1]
    $= 1891 \times 30(days) \times 24(hrs)/10E6 = 1.36GWh$
  - Using Equation 5.5.2 [2]
    = 6 (hm^3) × 50 (m) × 0.5 × 9.8 (m/s^2) × 1000 (kg/m^3) / (1000 × 1000) = 1.47 GWh
- Water losses are taken to be 0 for groundwater pumping since any loses in piping are assumed to go back to the aquifer.

5.4 Costs

Groundwater pumping costs involve investment of the well and pumping system and the operation and maintenence costs. Well construction costs will depend on a number of factors such as the drilling method used, geology, depth to aquifer, size of borehole, pumping volume etc. Pumping operation costs in general are to a large part dictated by the energy needed to pump the water up, which in turn depends on the depth of the water table.

Hernandez(2010) [27] citing a study by the Spanish ministry of the Environment estimates average groundwater abstraction costs varying from 0.08 Eur/m^3 for urban water supply to 0.12 Eur/m^3 for irrigation. However, values vary greatly depending on the factors mentioned above from location to location and are estimated to range from 0.03 Eur/m^3 in Guadiana to 0.37 Eur/m^3 in the Northern river basins for urban water supply. Similarily, for irrigation, groudwater abstraction costs are estimated to vary from 0.04 Eur/m^3 in Guadiana to 0.74 Eur/m^3 in the Segura river basin.

Operation and Maintenence Costs

Currently in Spain there is little awareness of carrying out perventive maintenence costs for groundwater pumping with most users waiting till after damage causes an interupption in water supply before taking action [30]. However, according to Mora,2013 [30] preventive maintenence provide several advantages such as better energy and cost efficiency throughout the life time of the pumps, lower overall maintence costs and better security of water supply.

Mora 2013 [30] calculates the preventive maintenence costs for 22 different pumping stations in south eastern Spain (Murcia and Alicante). The preventive maintenence costs $C_M(Eurs)$ are calculated in the non-linear relationship shown in Equation 5.4.1 where C_{cr} is the costs associated with the crane and removal of the piping, C_{ws} is the costs associated with the workshop, P_{hn} are the nominal hydraulic power supplied, L is the length of the pumping pipe and A, B and C are coefficients of the fitted relationship.

$$C_M(Eur) = C_{cr} + C_{ws} = AL^2 + BL + C + 14.693P_{hn} + 737.98 \tag{5.4.1}$$

The maintenence cost per cubic meter is calculated then calculated using an average lifetime of 8,000 working hours. Table 5.3 is a reproduction of some of the key results for the 22 different pumping stations in the study [30].

Table 5.3: Example groundwater pump parameters in Spain [30]

Pump ID	Flow (m3/h)	Head (m)	Nominal Engine Power (kW)	Hours (h/yr)	Age (yr)	Pipe Diameter (mm)	Pipe Length (m)	Wire Section (mm2)
P.1.1	238	200	219	3,676	4	200	207	185
P.1.2	299	160	191	3,676	5	200	240	150
P.1.3	342	298	370	6,942	7	200	336	150
P.1.4	288	115	138	3,563	17	250	137	70
P.1.5	299	260	295	3,676	1	200	276	150
P.1.6	360	301	520	2,072	21	250	352	150
P.1.7	360	357	520	8,727	21	250	362	150
P.1.8	360	297	440	5,954	0.5	250	220	150
P.1.9	630	103	520	3,563	17	300	148	90
P.2.1	240	200	177	8,067	12	200	102	150
P.3.1	45	90	15	3,159	2	200	90	10
P.3.2	120	83	37	3,191	2	200	95	10
P.3.3	120	62	30	3,160	2	200	105	16
P.4.1	720	155	423	7,225	14	300	140	150
P.4.2	720	155	423	7,162	14	300	140	150
P.4.3	900	120	423	7,050	14	300	140	150

Table 5.3: Example groundwater pump parameters in Spain [30]

Pump ID	Flow (m3/h)	Head (m)	Nominal Engine Power (kW)	Hours (h/yr)	Age (yr)	Pipe Diameter (mm)	Pipe Length (m)	Wire Section (mm2)
P.5.1	180	180	130	904	1	250	237	150
P.5.2	240	230	220	3,039	8	250	235	150
P.5.3	240	230	220	1,635	5	250	173	185
P.5.4	300	220	220	951	1	250	252	150
P.5.5	300	150	220	4,655	6	250	170	150
P.5.6	381	250	220	3,151	3	250	250	150
Average	349	192	271	3,910	8	241	200	128
Maximum	900	357	520	8,727	21	300	362	185
Minimum	45	62	15	904	1	200	90	10

Table 5.4: Example groundwater pump performance results in Spain [30]

Pump ID	Actual flow Q_c (m^3/h)	Actual head H_c (m)	Power at Panel P_{ac} (kW)	Power at Pump P_{hc} (kW)	Power Efficiency (%)	Cost Crane C_{cr} (€)	Cost Workshop C_{ws} (€)	Cost Maintenance C_M (€)	Cost Maintenance per Vol Water C_{Mv} ($c€/m^3$)
P.1.1	67.4	237.53	145.3	43.63	30.02	3,209	2,641	5,850	0.61
P.1.2	78.9	267.2	210.9	57.45	27.24	3,541	2,652	6,193	0.61
P.1.3	178.6	326.48	356.4	158.89	44.58	4,472	4,819	9,290	0.49
P.1.4	230.9	111.19	122.6	69.96	57.06	2,805	2,064	4,869	0.24
P.1.5	250	308.88	311.4	210.42	67.57	3,898	3,848	7,746	0.39
P.1.6	250.1	339.05	432.9	231.07	53.38	5,526	5,077	10,603	0.52
P.1.7	300.8	372.74	474	305.53	64.46	5,643	5,884	11,527	0.46
P.1.8	395.1	250.35	438.9	269.54	61.41	3,903	5,019	8,922	0.27

Table 5.4: Example groundwater pump performance results in Spain [30]

Pump ID	Actual flow Q_c (m^3/h)	Actual head H_c (m)	Power at Panel P_{ac} (kW)	Power at Pump P_{hc} (kW)	Power Efficiency (%)	Cost Crane C_{cr} (€)	Cost Workshop C_{ws} (€)	Cost Maintenance C_M (€)	Cost Maintenance per Vol Water C_{Mv} ($c€/m^3$)
P.1.9	534.8	110.2	311.8	160.6	51.51	3,341	3,326	6,667	0.15
P.2.1	106.6	107.08	66.7	31.11	46.63	2,087	2,660	4,747	0.28
P.3.1	44.5	58.29	16.7	7.07	42.33	1,954	900	2,855	0.54
P.3.2	42.7	75.43	24.8	8.78	35.39	2,010	1,137	3,147	0.44
P.3.3	59.85	78.2	25.7	12.75	49.63	2,120	1,036	3,156	0.66
P.4.1	567	153.3	410.7	236.86	57.67	3,228	5,206	8,434	0.16
P.4.2	538.8	151.1	457.1	221.85	48.53	3,228	5,206	8,434	0.17
P.4.3	468.3	154.55	500.5	197.22	39.41	3,228	5,062	8,290	0.18
P.5.1	101.52	236.51	120.5	65.43	54.3	4,121	2,035	6,156	0.73
P.5.2	182.2	213.6	211.8	106.05	50.07	4,095	2,948	7,044	0.42
P.5.3	210.6	198.11	218	113.69	52.15	3,288	2,948	6,236	0.33
P.5.4	222.12	233.66	261.8	141.43	54.02	4,311	3,381	7,691	0.39
P.5.5	283.7	158	191.15	122.15	63.9	3,248	2,540	5,788	0.25
P.5.6	337	252.12	422	231.53	54.86	4,286	4,552	8,837	0.33
Average	247.8	199.71	260.53	134.85	50.28	3,525	3,406	6,931	0.39
Maximum	567	372.74	500.5	305.53	67.57	5,643	5,884	11,527	0.73
Minimum	42.7	58.29	16.7	7.07	27.24	1,954	900	2,855	0.15

Total operation and maintenence costs without considering the costs for energy for 4 different groundwater pumps in Robinson 2002 [1] are summarized in Table 5.5. In the last two colums the values have been converted to costs in c€/m^3 as well as c€/m^3/m for comparison with other studies. As seen the values of OnM costs are relatively very small.

Table 5.5: Groundwater system maintenence costs in Australia [1]

Bore ID	Yield (ML/day)	Pumping Days	Engine Type	Pump Type	Cost OnM (USD/hr)	Cost OnM (€/L)	Cost OnM w/o fuel ($c€/m^3$	Cost OnM w fuel ($c€/m^3$
B1	25	70.00	Electric 185kW	Turbine Pump	0.34	2.9e-07	0.029	2.51
B2	25	70.00	Diesel 190kW	Turbine Pump	0.43	3.7e-07	0.037	3.45
B3	10	70.00	Electric 75kW	Turbine Pump	0.3	6.5e-07	0.065	1.72
B4	10	70.00	Diesel 70kW	Turbine Pump	0.3	4.2e-07	0.065	2.37

Investment Costs

Investment costs for groundwater pumping systems, considering an interest rate of 4% and a lifetime of 15 years results in an annuity of about 0.02 Eur/m^3 (about 10 times less than a desalination plant).

Hernandez(2010) [27] provide estimates of construction costs for different well depths and pumping capacities in different regions of Spain as reproduced in Table 5.6 below.

Table 5.6: Installation cost of groundwater systems in Spain [27]

Parameter	La Mancha	Planas levantinas	Campo de Dalias (Almeria)	Llano de Palma (Mallorca)
Depth of well(m) Min	100	60	150	30
Depth of well(m) Max	200	160	400	70
Pumping Capacity (L/s)	50	60	100	10
Total cost (1,000 Eurs) Min	50	25	94.2	13.9

Table 5.6: Installation cost of groundwater systems in Spain [27]

Parameter	La Mancha	Planas levantinas	Campo de Dalias (Almeria)	Llano de Palma (Mallorca)
Total cost (1,000 Eurs) Max	79.8	51.4	218.8	18.4

Normalizing these values we can get an estimated range of the costs of installing groundwater systems for different depths and pumping capacity. The normalized chart is presented below in Table 5.7

Table 5.7: Normalized groundwater system installation costs in Spain (original data from [27])

Bore ID	Depth (m)	Cap (L/s)	Cap (hm3/month)	Cost (1000 Eur)	Cost (Eur/(L/s))	Cost (Eur/m)	Cost (Eur/(L/s)/m	Cost (Eur/(hm3/month) m)
B1	100	50	0.13	50	1,000	500	10	3,858
B2	200	50	0.13	79.8	1,596	399	8	3,079
B3	60	60	0.156	25	417	416.7	6.9	2,679
B4	160	60	0.156	51.4	857	321.3	5.4	2,066
B5	150	100	0.259	94.2	942	628	6.3	2,423
B6	400	100	0.259	218.8	2,188	547	5.5	2,110
B7	30	10	0.026	13.9	1,390	463.3	46.3	17,876
B8	70	10	0.026	18.4	1,840	262.9	26.3	10,141
Average	146.3	55	0.1	68.9	1,278.7	442.3	14.3	5,528.9

[1] Capital costs of installing a groundwater pump depends on a number of items including pumping capacity, bore depth, system design, materials used, engine type, proximity to electric power and water discharge area [1]. The major cost components are the bore casing, screens, pump, motor, protection, power connection and installation costs. An example of shallow groundwater borhole is given from the "Wakool Subsurface Drainage Scheme" consisting of 12 boreholes with an everage depth of $30m$. The capital cost per borehole is given as $\$89,000$, of which $\$54,500$ was for well construction and $\$34,500$ for power connection. For deep boreholes a large range is given varying from $\$90,000$ $(10ML/day, 140mdepth)$

to about \$320,000(25ML/day, 300m depth). Costs of energy connection will vary greatly by location and country but in Australia estimates from the Great Southern Energy are given as ranging from \$23,000 - \$28,000 ($< 90kW$ power requirement) to about \$35,000 - \$40,000 ($> 90kW$). Total capital costs for 4 different groundwater pumps in the study are summarized in Table 5.8. The values are normalized and converted to €in le 5.9 for comparison with other values in this study.

Table 5.8: Groundwater system Capital costs in Australia [1]

Bore ID	Bore Type	Depth(m)	Pumping Head (m)	Yield (ML/day)	Pumping Days	Engine Type	Pump Type	Cost (USD)
B1	20"x16"	220	45	25	70	Electric 185kW	Turbine Pump	222844.00
B2	20"x16"	220	45	25	70	Diesel 190kW	Turbine Pump	111271.00
B3	12"x9"	140	30	10	70	Electric 75kW	Turbine Pump	111271.00
B4	12"x9"	140	30	10	70	Diesel 70kW	Turbine Pump	106731.00

Table 5.9: Normalized/converted Groundwater capital cost parameters in Australia (original data from Robinson 2012 [1])

Bore ID	Cost (1000e)	Yield (L/s)	Capacity (hm^3 / $month$)	Cost (€/(L/s))	Cost (€/m)	Cost (€/ $(L/s)/m$)	Cost (€/ $(hm^3/month)$ / m)
B1	212.25	289.35	0.75	733.5	964.8	3.3	1286.30
B2	200.56	289.35	0.75	693.1	911.6	3.2	1215.30
B3	100.14	115.74	0.3	865.2	715.3	6.2	2384.40
B4	96.058	115.74	0.3	829.9	686.1	5.9	2287.10

Table 5.9: Normalized/converted Groundwater capital cost parameters in Australia (original data from Robinson 2012 [1])

Bore ID	Cost (1000e)	Yield (L/s)	Capacity (hm^3 / $month$)	Cost (€/(L/s))	Cost (€/m)	Cost (€/ (L/s)/m)	Cost (€/ ($hm^3/month$) / m)
Average	NA	NA	NA	780.46	819.46	4.65	1793.30

5.5 Energy Consumption

The study from south eastern Spain [30] which looks at 22 groundwater pumps can be used to calculate energy output in kWh per m^3 of water using the performance values of actual flow Q_c (m^3/h), power at panel P_{ac} (kW) and operation hours per year (h/yr) from Table 5.3. This is shown in Table 5.10.

Table 5.10: Calculated parameters for groundwtaer pumps in Spain

Pump ID	Flow per year (m^3)	Energy per year (KWh)	Energy per m^3 (kWh/m^3)
P.1.1	25,679	55,359	2.16
P.1.2	19,725	52,725	2.67
P.1.3	39,292	78,408	2
P.1.4	727,566	386,313	0.53
P.1.5	750	934	1.25
P.1.6	62,525	108,225	1.73
P.1.7	75,200	118,500	1.58
P.1.8	59,265	65,835	1.11
P.1.9	180,228	105,077	0.58
P.2.1	26,876	16,816	0.63
P.3.1	18,779	7,047	0.38
P.3.2	9,886	5,742	0.58
P.3.3	3,283	1,410	0.43
P.4.1	2,430,162	1,760,260	0.72
P.4.2	2,452,618	2,080,719	0.85

Table 5.10: Calculated parameters for groundwtaer pumps in Spain

Pump ID	Flow per year (m^3)	Energy per year (KWh)	Energy per m^3 (kWh/m^3)
P.4.3	4,138,367	4,422,918	1.07
P.5.1	33	40	1.19
P.5.2	1,804	2,097	1.16
P.5.3	2,154	2,230	1.04
P.5.4	2,761	3,254	1.18
P.5.5	222	149	0.67
P.5.6	448,116,314	561,142,684	1.25
Average	263,135,599	276,653,420	1.05
Maximum	448,116,314	561,142,684	2.67
Minimum	33	40	0.38

Robinson 2002 [1] presents Equation 5.5.1 relating power required for pumping $P(kW)$ with the flow rate $R(L/s)$, pumping head $H(m)$, pump efficiency E_p (%) and derating efficiency E_d (%).

$$P = (R \times H)/(102 \times E_p \times E_d) \quad (5.5.1)$$

The results of the required power are shown in Table 5.11.

Table 5.11: Groundwater system Capital costs in Australia [1]

Bore ID	Bore Type	Depth(m)	Pumping Head (m)	Yield (L/s)	Pumping Days	Pump Efficiency (%)	Derating (%)	Power Required (kW)
B1	20"x16"	220	45	289.35	70	80.00	80	199.46
B2	20"x16"	220	45	289.35	70	80.00	75	212.76
B3	12"x9"	140	30	115.74	70	80.00	80	53.19
B4	12"x9"	140	30	115.74	70	80.00	75	56.74

Another study from 2007 [2] presents another Equation 5.5.2 relating the energy required for pumping $E(MWh)$ with the volume of water pumped $W(hm^3)$, pumping head $h(m)$, and a coefficient ϕ. The coefficient term constitutes the pump efficiency γ, water density ρ (kg/m^3) and gravity $g(m/s^2)$.

$$E = \phi \times W \times h \tag{5.5.2}$$

Where:

- $\phi = \gamma \times \rho \times g/1000$
- γ = between 0.4 to 0.7
- $\rho = 1000\ kg/m^3$
- $g = 9.8\ m/s^2$

Efficiency and Waste water

Water lost in groundwater pumping is considered as returned to the aquifer so water losses are considered Null. The energy lost in pumping water that does not reach the top is considered in the pumping efficiency.

5.6 Existing Resources

Groundwater data was downloaded from the Spanish Ministry of the environment [32]. There are several different groundwater aquifers as shown in Figure 5.1. For this analysis we consider management of the groundwater bodies by each river basin and assume that aquifers are not shared across river basin boundaries. 2798 piezometers were listed in the ministry database as shown in Figure 5.2 with monthly data available for several years. Data before 2002 was scarce and so data for the 10 years between 2003 and 2012 was analzyed.

Inverse distance weighting (IDW) was used to interpolate the different piezometer readings spatially. The grid size and piezometer locations are shown in Figure 5.3. Figure 5.4 and Figure 5.5 shows the data available from different piezometers for each month in 2003 and 2012. It is clear that data collection became more extensive in the later years.

Results of the IDW interpolation are shown in Figure 5.6 and Figure 5.7 for each month in 2003 and 2012. As we can see, from available data, the north western parts of Spain have high water levels (0m to 50m), while the south eastern parts of Spain have lower water tables (50m-100m), with lowest levels in the Segura river basin (100m and below).

Keeping in mind the available locations of piezometers, we can analyze in different charts to see variations across months, years and river basins. Figure 5.8 shows boxplots of ground water levels averaged across river basins for each month from 1 to 12 for the years 2003 to 2012. As seen in the maps above we see low groundwater levels in the south eastern basins (in particular Segura). There are no strong seasonal patterns in the groundwater levels. Figure 5.9 shows a bar chart with individual piezometer levels for the different basins. In this chart we can see that in some basins as we approach 2012 certain piezometers (in Segura, Guadaluquivir, Guadiana) show lower groundwater levels, meaning extraction at certain points within these basins has been increasing.

Finally the ministy of environment also provides a list of over exploited aquifers as shown in Figure 5.10. We see that the low water level location in the interpolation maps in Figure 5.6 and Figure 5.7 correspond to the over-exploited aquifers in Figure 5.10.

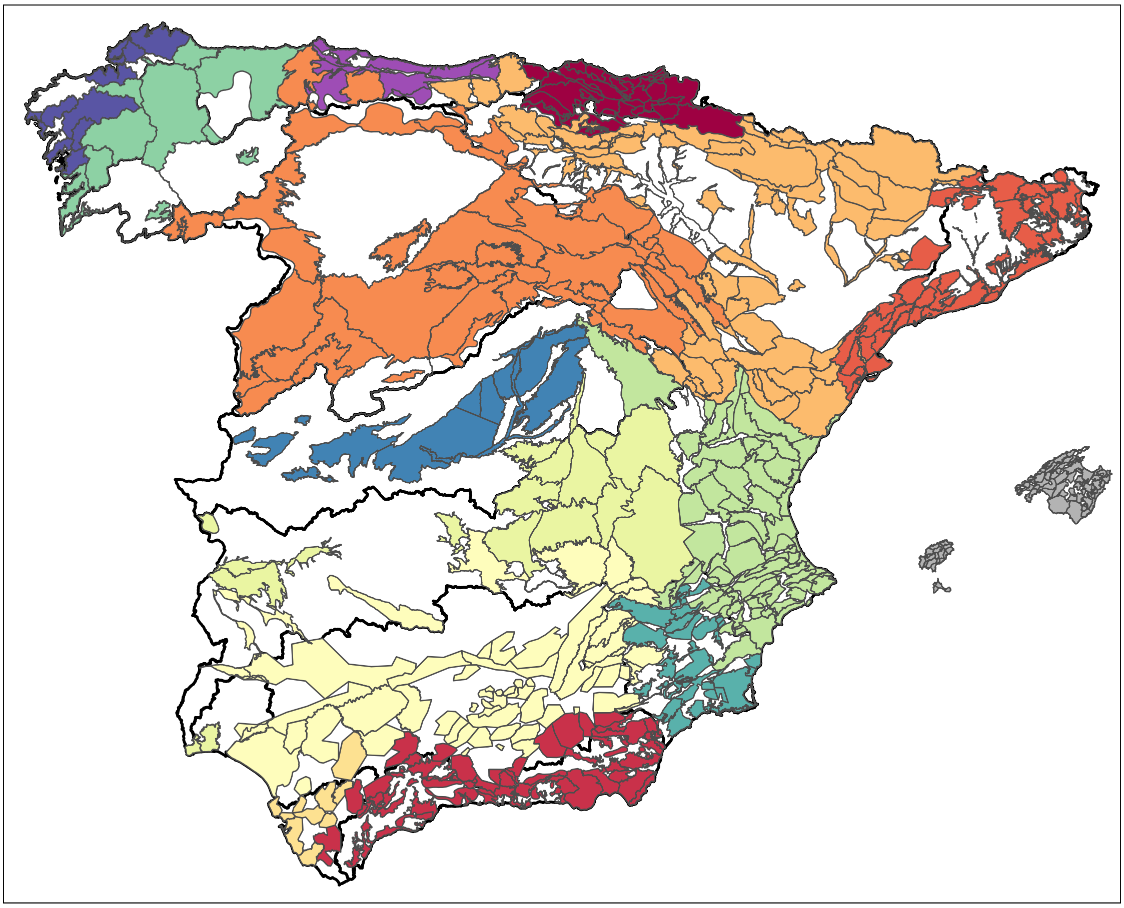

Figure 5.1: Groundwater aquifers in Spain

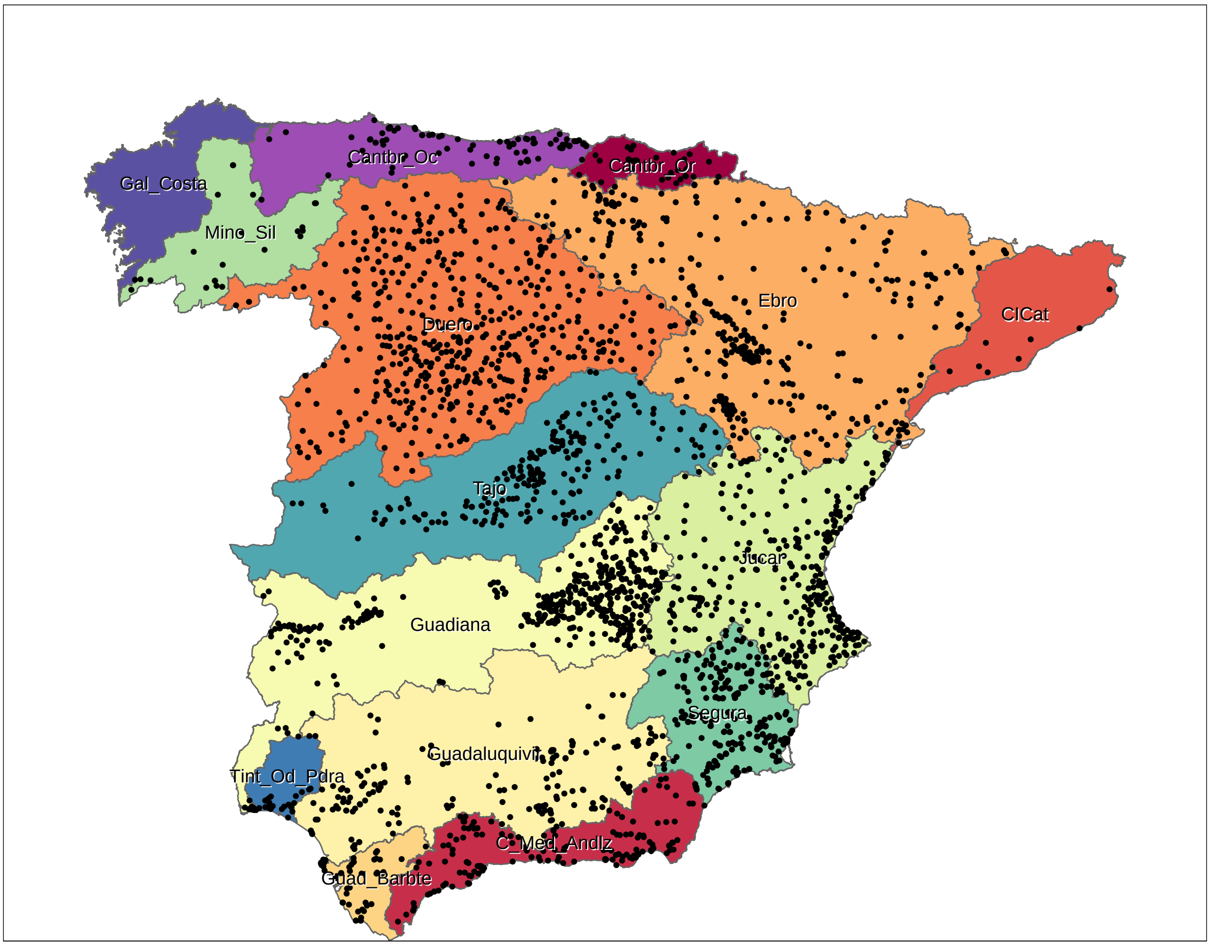

Figure 5.2: Ministry of environment piezometer locations in Spain

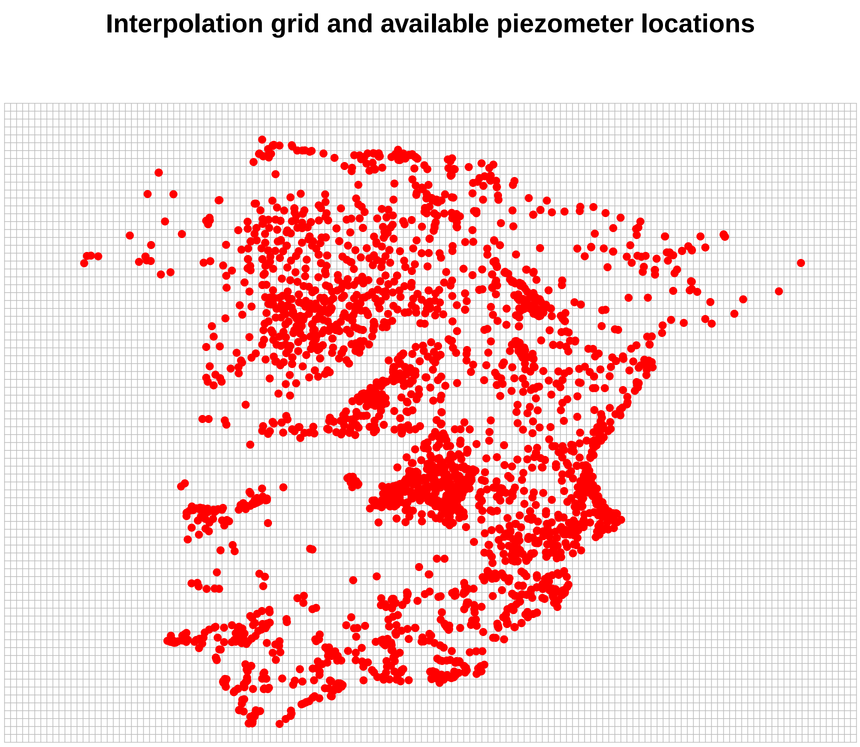

Figure 5.3: piezometer locations and interpolation grid

Figure 5.4: piezometer data available for 2003

piezometers Available for Year_Month

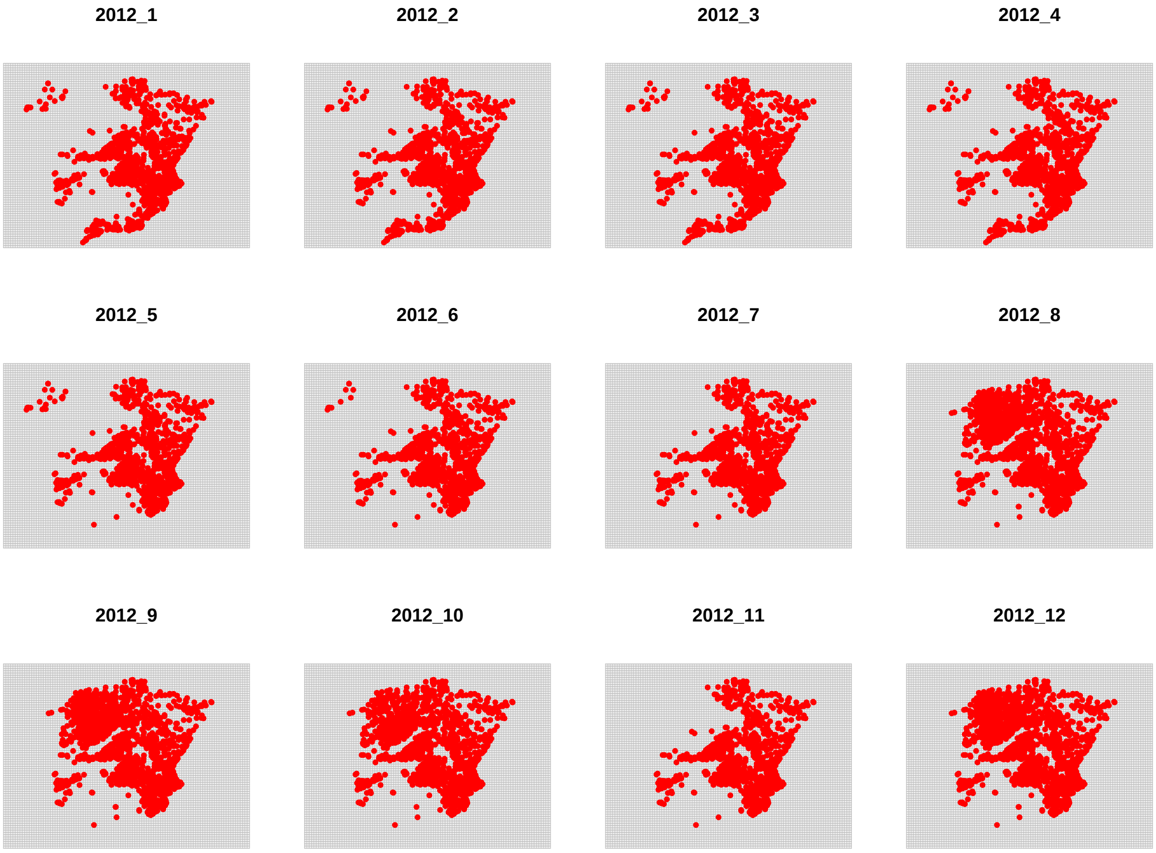

Figure 5.5: piezometer data available for 2012

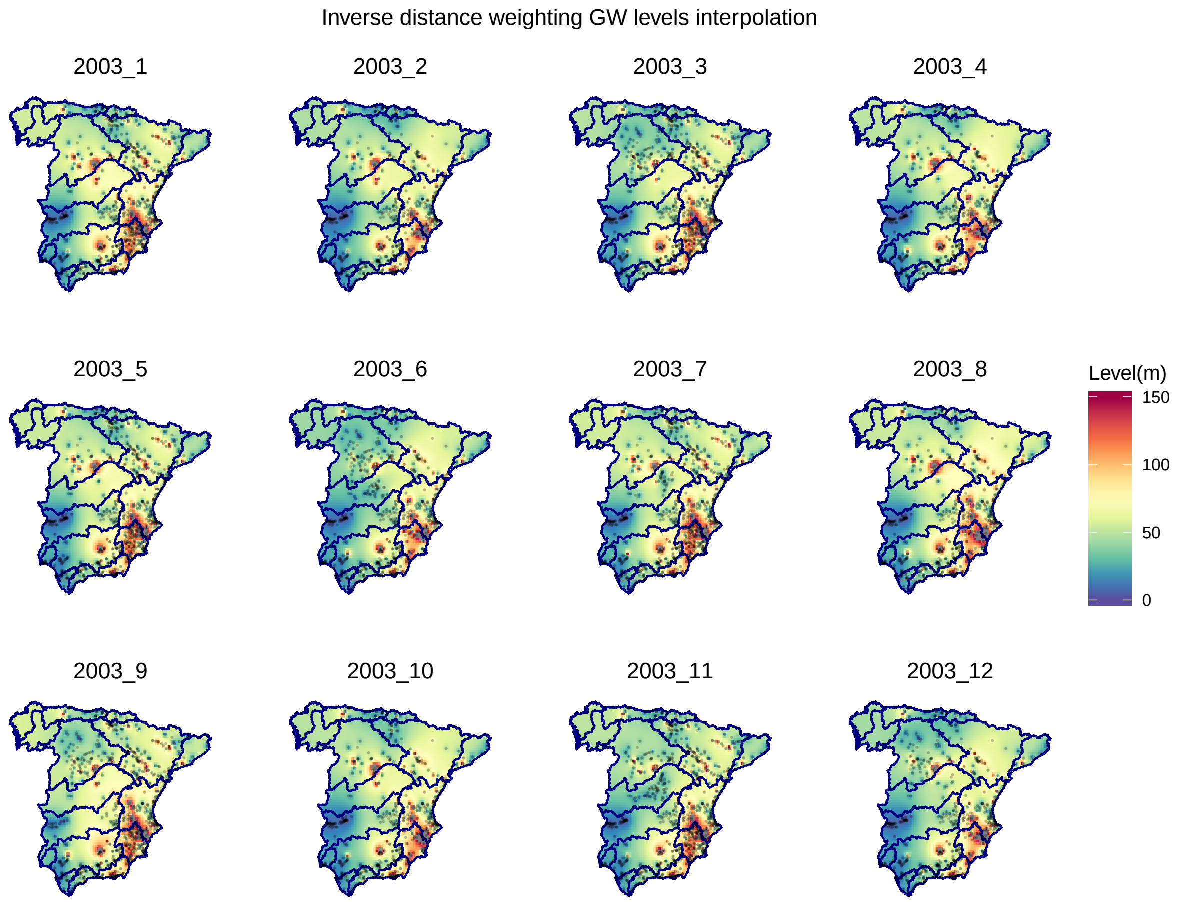

Figure 5.6: Inverse distance weighting interpolation for 2003 GW levels

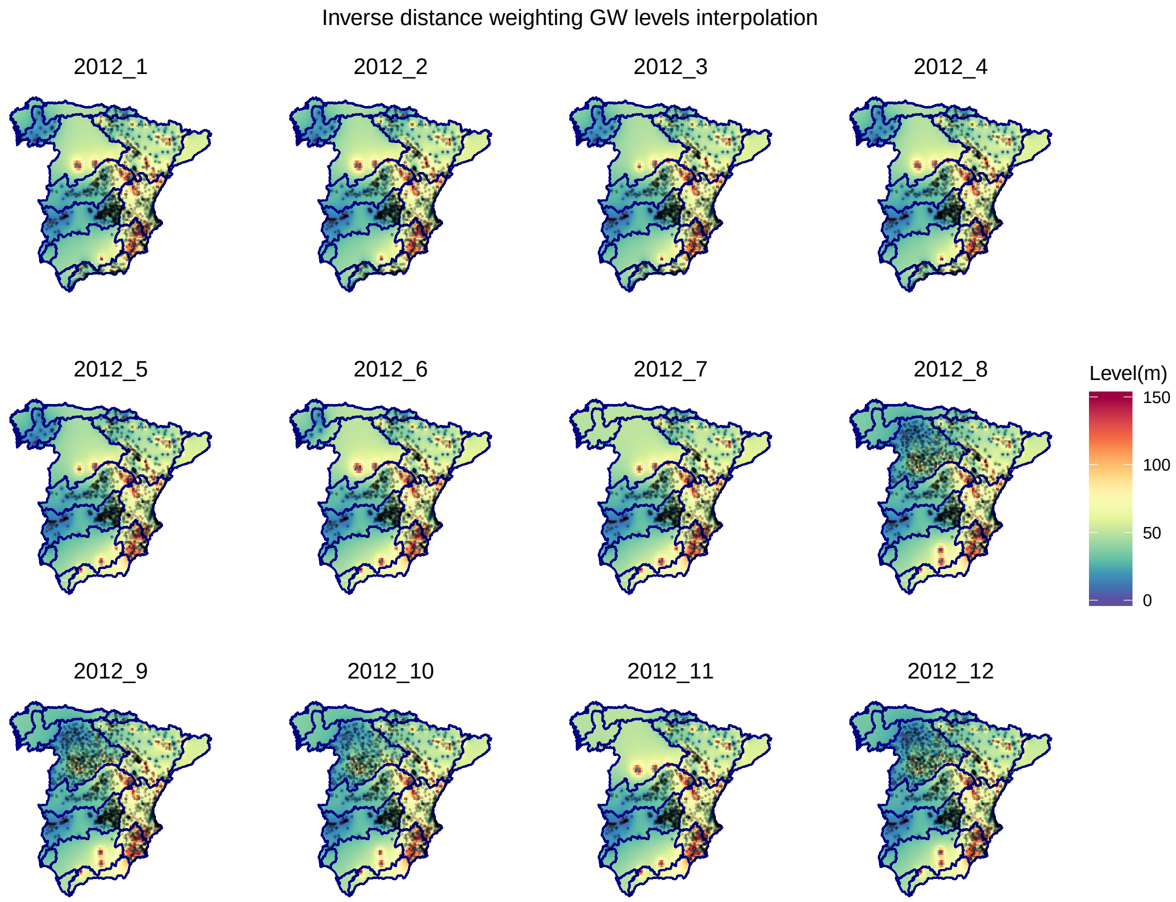

Figure 5.7: Inverse distance weighting interpolation for 2012 GW levels

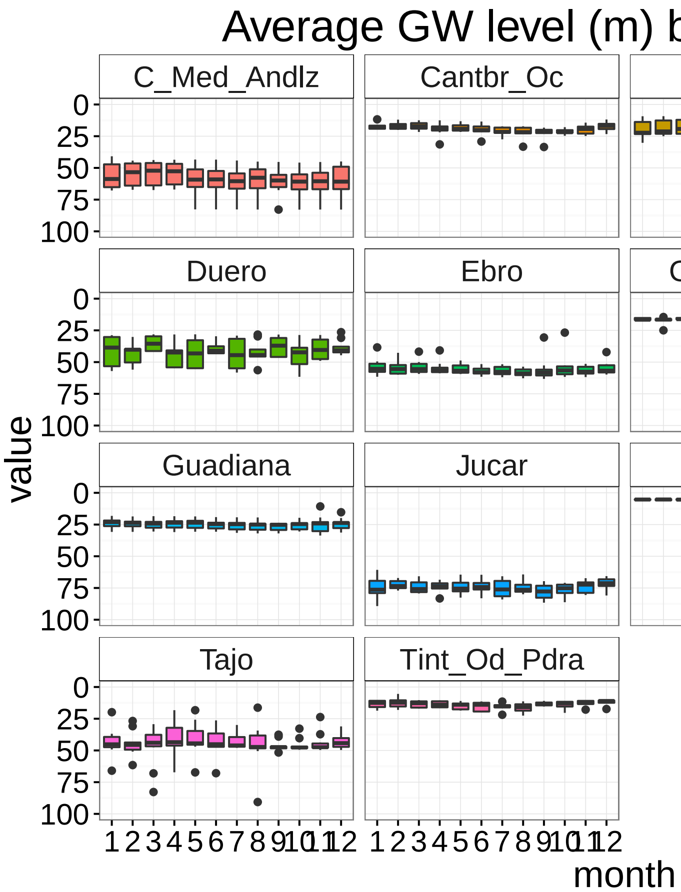

Figure 5.8: Boxplot of monthly GW levels averaged over river basins (2003-2012)

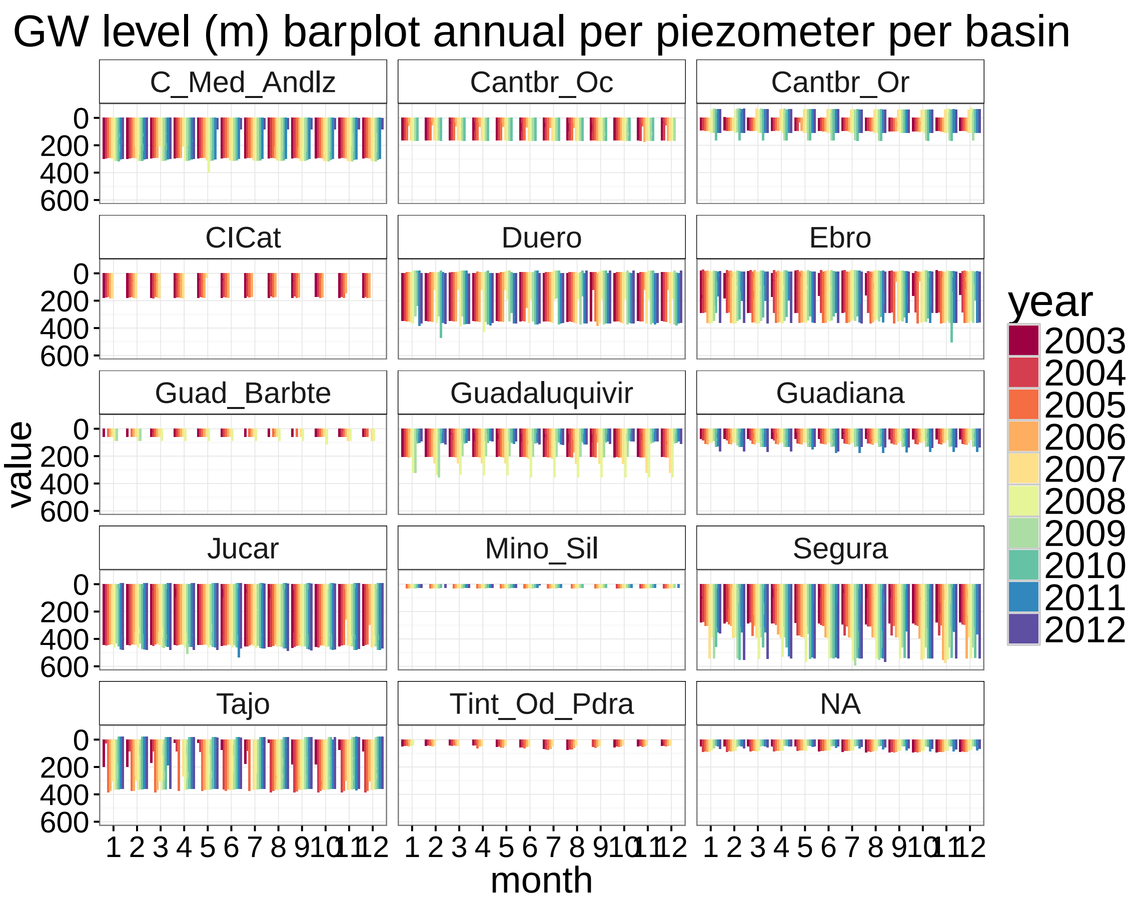

Figure 5.9: Barplot of monthly GW levels for invdividual piezometers per river basin (2003-2012)

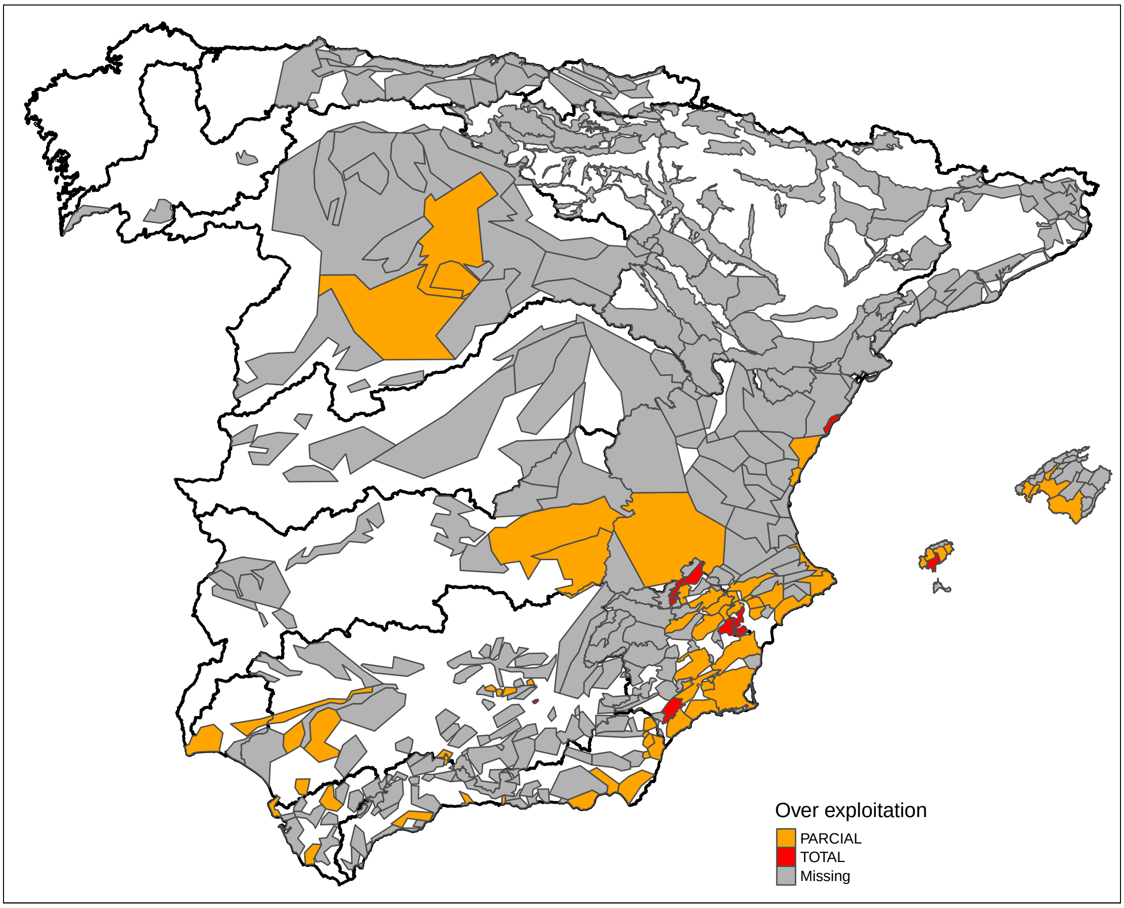

Figure 5.10: Overexploited aquifers from ministry of enviroment webstie, (accessed Feb 2016)

5.7 Existing Capacity

There is limited data and it is difficult to account for groundwater pumping around the country as a result of undocumented wells and ilegal pumping. One source from 2000, the White book of Water [33] provides some baseline values to get an estimate. Some values of groundwater recharge and pumping rates from the White book are shown in Table 5.12. The model uses the new administrative boundaries of the river basins and the values have been distributed according to the new names and basins as shown in Table 5.13. The only change in the numbers has been in the distribution of the Guadalquivir Basin into Guadalquivir and guadalate y barbate. The resources have been distributed proportionately to the areas of the new distributions.

Table 5.12: Groundwater recharge and pumping [33]

Basin	Rainfall-ETP (hm^3/yr)	Natural Recharge (hm^3/yr)	Pumping (hm^3/yr)	% of Recharge	% of Natural Resources	Pumping Capacity (L/s)	Pumping Capacity ($hm^3/month$)
Norte I	12,689	2,745	0	0	0	0	0
Norte II	13,881	5,077	19	0.4	0.1	610.9	1.6
Norte III	5,337	894	33	3.7	0.6	1,061	2.8
Duero	13,660	3,000	371	12.4	2.7	11,927.7	30.9
Tajo	10,883	2,393	164	7.9	1.5	5,272.6	13.7
Guadiana I	4,414	687	738	107.4	16.7	23,726.9	61.5
Guadiana II	1,061	63	76	120.6	7.2	2,443.4	6.3
Guadalquivir	8,601	2,343	507	21.6	5.9	16,300.2	42.3
Sur	2,351	680	420	61.8	17.9	13,503.1	35
Segura	803	588	478	81.3	59.5	15,367.8	39.8
Jucar	3,432	2,492	1,425	57.2	41.5	45,814	118.8
Ebro	17,967	4,614	198	4.3	1.1	6,365.7	16.5

Table 5.12: Groundwater recharge and pumping [33]

Basin	Rainfall-ETP (hm^3/yr)	Natural Recharge (hm^3/yr)	Pumping (hm^3/yr)	% of Recharge	% of Natural Resources	Pumping Capacity (L/s)	Pumping Capacity ($hm^3/month$)
Catalunya	2,787	909	424	46.6	15.2	13,631.7	35.3
Galicia	12,250	2,234	0	0	0	0	0
Total	110,116	28,719	4,853	16.9	4.4	156,024.9	404.4

Table 5.13: Groundwater recharge and pumping modified for new River Basins [33]

Basin	Rainfall-ETP (hm^3/yr)	Natural Recharge (hm^3/yr)	Pumping (hm^3/yr)	% of Recharge	% of Natural Resources	Pumping Capacity (L/s)	Pumping Capacity ($hm^3/month$)
Mino_Sil	12,689	2,745	0	0	0	0	0
Cantbr_Oc	13,881	5,077	19	0.4	0.1	610.9	1.6
Cantbr_Or	5,337	894	33	3.7	0.6	1,061	2.8
Duero	13,660	3,000	371	12.4	2.7	11,927.7	30.9
Tajo	10,883	2,393	164	7.9	1.5	5,272.6	13.7
Guadiana	4,414	687	738	107.4	16.7	23,726.9	61.5
Tint_Od_Pdra	1,061	63	76	120.6	7.2	2,443.4	6.3
Guadalquivir	7,794	2,123	459	21.6	5.9	14,770	38.3
Guad_Barbte	807	220	48	21.6	5.9	1,530	4
C_Med_Andlz	2,351	680	420	61.8	17.9	13,503.1	35
Segura	803	588	478	81.3	59.5	15,367.8	39.8

Table 5.13: Groundwater recharge and pumping modified for new River Basins [33]

Basin	Rainfall-ETP (hm^3/yr)	Natural Recharge (hm^3/yr)	Pumping (hm^3/yr)	% of Recharge	% of Natural Resources	Pumping Capacity (L/s)	Pumping Capacity ($hm^3/month$)
Jucar	3,432	2,492	1,425	57.2	41.5	45,814	118.8
Ebro	17,967	4,614	198	4.3	1.1	6,365.7	16.5
CICat	2,787	909	424	46.6	15.2	13,631.7	35.3
Gal_Costa	12,250	2,234	0	0	0	0	0
Total	110,116	28,719	4,853	16.9	4.4	156,024.9	404.4

CEDEX 2010 [34] gives some predictions of the percentage changes in recharge levels for the different river basins as shown in Table 5.14. Values for Tinto, Odiel and Piedras and Guadalete and Barbate river basins were not given but the same percentages as in Guadiana and Guadalquivir respectively have been used. The prediction are the averaged values of different six different models (CGCM2-FIC, ECHAM4-FIC, HadAM3-FIC, HadCM3-SDSM, ECHAM4-RCAO, HadCM3-PROMES) and correspond to two of the IPPC climate change scenarios A2 and B2. The models consider three different time periods as shown in the Table (2011-2040, 2041-2070, 2071-2100).

Table 5.14: Percentage changes in groundwater recharge due to climate change [34]

Basin	2011-2040 A2	2011-2040 B2	2041-2070 A2	2041-2070 B2	2071-2100 A2	2071-20100 B2
Mino_Sil	-7	-5	-12	-10	-21	-11
Cantbr_Oc	-10	-8	-14	-14	-26	-16
Cantbr_Or	-9	-7	-13	-13	-27	-18
Duero	-8	-8	-17	-10	-33	-14
Tajo	-8	-9	-20	-9	-39	-18
Guadiana	-14	-12	-30	-12	-46	-24
Tint_Od_Pdra	-14	-12	-30	-12	-46	-24

Table 5.14: Percentage changes in groundwater recharge due to climate change [34]

Basin	2011-2040 A2	2011-2040 B2	2041-2070 A2	2041-2070 B2	2071-2100 A2	2071-20100 B2
Guadalquivir	-13	-15	-28	-15	-42	-25
Guad_Barbte	-13	-15	-28	-15	-42	-25
C_Med_Andlz	-12	-17	-29	-15	-40	-27
Segura	-9	-13	-20	-14	-33	-21
Jucar	-3	-12	-16	-12	-31	-23
Ebro	-7	-7	-11	-11	-24	-14
CICat	0	-6	-4	-7	-19	-14
Gal_Costa	-8	-6	-12	-10	-20	-11
Total	-8	-8	-15	-12	-27	-16

5.8 Storage

5.9 Future Predictions and Climate Change

Chapter 6

Desalination

6.1 Key Points

6.2 Introduction

In this section we discuss desalination in Spain and the inputs used in the model. Several different studies [35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52] were used to calculate the different desalination parameters used in the model. The parameters are summarized in Table 6.1 and Table 6.2.

Desalination technologies can be divided into thermal desalination (Multi stage flash (MSF), Multi-effect distillation (MED), Thermal Vapour Compression distillation (TVC)) and membrane based technologies (Reverse Osmosis (RO), Mechanical Vapour Compression (MVC), Nanofiltration (NF) and Electrodialysis (ED))[35]. The choice of one type of technology over the other depends on a number of factors including feed water salinity, required quality, energy cost and local demand for electricity. Globally about 60% of installed technologies are Reverse Osmosis and 30% is Multi-stage flash technologies[37]. The greatest share of desalination technologies is installed in the Middle East (about 38%[37]) mostly dominated by thermal processes owing to the cheap cost of fossil fuel based energy. In Europe, Spain has the highest share (about 8% of global share[37]) of installed desalination capacity, a majority of which is membrane-based Reverse Osmosis technologies. In spain desalination is primarily used along the water scarce mediterranean coastal regions and islands to meet water demand pressures from tourism and agriculture.

Desalination in Spain became popular due to the policies put forth in the National Hydrological Plans (NHP) as part of the Spanish AGUA program which replaced the Ebro

Inter-basin transfer plans after the change of government in 2005. The new program proposed to locally produce about 1000 hm^3 of water resources from improved water infrastructure and irrigation systems, water reuse and desalination.

The two most popular desalination technologies, Reverse Osmosis (RO) and Multi Stage Flash (MSF) were considered for seawater (SW). Reverse Osmosis was also considered for inland brackish water (BR). Thus, the technologies are represented by BRRO (Brackish water Reverse Osmosis), SWRO (Seawater Reverse osmosis) and SWMSF (Seawater Multi Stage Flash). The energy consumption values given for thermal energy consumption in MSF technologies in Table 6.3 [42] appear to be higher than in the other studies considered, Table 6.4 [47] and Table 6.10 [51], and were thus not included in the final selection. The remaining parameteres are the rounded averaged values of the different studies. The investment costs are based on an average of the values and methods given in several different studies described in more detail below [52, 38, 37]. Investment costs have been calculated as the average amortization costs in $Eurs/m^3$. Using these rates we can calculate total annual investment costs as the amortization costs $Eurs/m^3$ times the m^3 of water produced per year. Assuming plants are operating at full capacity this would be the additional capacity in $Eurs/(m^3/day)$ needed times 365. Other studies use non-linear relationships of investments with capacity as given in the Fritzmann study from 2007 [35]. Ratio's of cost differences between BRRO, SWRO and MSF were used from different studies to estimate values when not given.

6.3 Parameter Summary

Table 6.1: Desalination parameters used in model

Parameter	Name in Model	BRRO	SWRO	SWMSF
Energy Consumption (kWh/m3)	p_nrg_dsal(dsal)	3	5	20
Water loss (%)	p_wloss_dsal(dsal)	0.35	0.55	0.2
Cost O&M (Eur/m3)	p_cost_dsal_OnM(dsal)	0.15	0.3	0.5
Cost Investment (Eur/m3)	p_cost_dsal_Inv(dsal)	0.11	0.16	0.30

Notes:
1:O&M costs exclude energy costs which are assumed to be 40% of RO costs and 50% of MSF costs.

The existing installed capacity of desalination plants is provided in Table 6.2. Distribtion of desalination plants by county was downloaded from the website of the Spanish ministry of the environment [44]. The map of the different counties were then overlayed by the river basin map and the clipped to extract how much desalination capacity was located in each river basin. This is shown in Figure 6.1. Capacity located in counties without a coast were considered brackish water (BR) plants, while those located in counties with a coast were considered seawater (SW) plants. All the capacity is assumed to be Reverse Osmosis (RO).

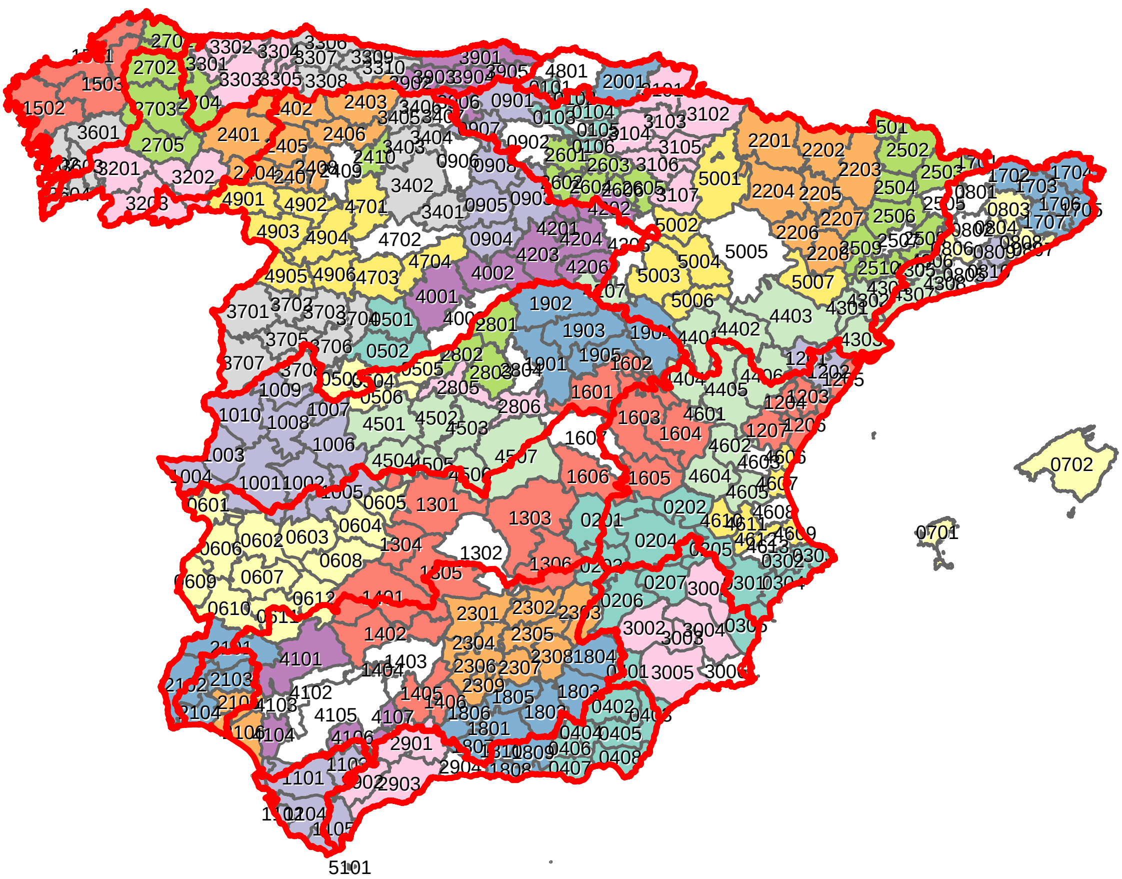

Figure 6.1: Spain county map overlay with river basins

Table 6.2: Distributed desalination capacity (m3/day)

Label	Area (km2)	Coast (km)	BRRO (m3PerDay)	SWRO (m3PerDay)	Total (m3PerDay)	Desal
Gal_Costa	13,217	2,120	16,000	1,472	17,472	
Mino_Sil	17,592	0	170,020	0	170,020	
Cantbr_Oc	17,436	807	16,000	1,340	17,340	
Cantbr_Or	5,807	266	0	616	616	

Table 6.2: Distributed desalination capacity (m3/day)

Label	Area (km2)	Coast (km)	BRRO (m3PerDay)	SWRO (m3PerDay)	Total Desal (m3PerDay)
Duero	78,860	0	10,003	0	10,003
Tajo	55,764	0	73,913	0	73,913
Guadiana	55,389	34	24,468	300	24,768
Tint_Od_Pdra	4,751	214	0	720	720
Guadaluquivir	57,228	73	23,960	0	23,960
Guad_Barbte	5,928	280	698	0	698
C_Med_Andlz	17,948	652	4,624	737,566	742,190
Segura	18,897	395	19,874	441,342	461,216
Jucar	42,958	588	50,730	696,788	747,518
Ebro	85,567	148	18,519	6,720	25,239
CICat	16,494	795	6,029	367,347	373,376
Total	120	93	434,838	2,254,211	2,689,049

6.4 Worked Example

6.5 Energy Consumption

With technological advances in the last few decades energy consumption of desalination has dramatically decreased by almost 90% from 1968 to 2009 [37]. A large part of this decrease has also been as a result of the shift to energy efficient Reverse Osmosis (RO) processes. In RO processes the majority of the energy consumption (about 80%) is by high-pressure pumping (55 to 68 bar in seawater desalination) to force feed water through the membrane. Another study [42] provides parameters related to the energy consumption by different desalination technologies as shown in Table 6.3. Another study [47] from 2010 gives similar energy consumption parameters reproduced in Table 6.4

Table 6.3: Desalination energy parameters

Technology	Capacity (m3/day)	Thermal energy (kWh/m3)	Electrical energy (kWh/m3)	Operation temperature (deg C)
Multi Stage Flash	4,000-450,000	55-220	4-6	90-120
Multi effect distillation	100-56,000	40-220	1.5-2.5	50-70
Mechanical Vapour Compression	5-17,000	-	6-12	50-70
Reverse Osmosis	0.01-360,000	-	2.8-12	<40!

Table 6.4: Desalination energy parameters 2010

Technology	Capacity (m3/day)	Electrical energy (kWh/m3)	Thermal Energy (kWh/m3)	Total Energy Consumption (kWh/m3)
Multi Stage Flash	50,000-70,000	4-6	9.5-19.5	13.5-25.5
Multi effect distillation	5,000-15,000	1.5-2.5	5-8.5	6.5-11
Mechanical Vapour Compression	100-2,500	7-12	-	7-12
Reverse Osmosis	24,000	3-5.5	-	3-3.5

6.6 Costs

In general the more salts there are to remove, the more costly is the process. Thus seawater desalination is more costly than brackish water which is not as saline [37]. A summary of estimates by Campos 2010 [37] for desalination costs of RO and MSF technologies by capacity is provided in Table 6.5 for both seawater(SW) and brackish water(BR). The same study also gives a breakup of the costs for the two technologies in percentages and Eur/m^3 as shown in Table 6.6.

Table 6.5: Desalination costs for RO and MSF processes

Technology	Capacity(m3/day)	Cost(Eur/m3)
Seawater MSF	23,000-528,000	0.42-1.40
SeaWater RO	<100	1.20-15.00
SeaWater RO	250-1,000	1.00-3.14
SeaWater RO	1,000-4,800	0.56-1.38
SeaWater RO	15,000-60,000	0.38-1.30
SeaWater RO	100,000-320,000	0.36-0.53
Brackish RO	<20	4.50-10.32
Brackish RO	20-1,200	0.62-1.06
Brackish RO	40,000-46,000	0.21-0.43

Table 6.6: Breakup of desalination costs for RO and MSF processes

Component	MSF(%)	RO(%)	MSF(Eur/m3)	RO(Eur/m3)
Energy-fuel	40.00	0.00	0.45	0.00
Energy-electricity	15.20	42.60	0.17	0.28
Chemicals	3.50	6.50	0.04	0.04
Chemical cleaning	0.20	0.30	0.00	0.00
Maintenance	2.70	4.70	0.03	0.03
Amortization	35.00	32.50	0.39	0.21
Labour	3.50	9.30	0.04	0.06
Membrane replacement	0.00	4.20	0.00	0.03
Total	100.00	100.00	1.12	0.65

Desalination investment costs depends on the size of the plant. The relationship of costs (1000 USD) with capacity (m^3/h) for seawater desalination can be given by Equation 6.6.1 [35]. Fritzmann 2007 [35] estimate a membrane replacement cost of 5% of total lifecycle costs or 0.11 Eur/m^3 to 0.29 Eur/m^3. Labour costs are estimated at 1.12 $Eur-cent/m^3$ or 1 to 1.5% of investment costs. Total life cycle costs of chemicals used for pre-treatment were estimated at about 0.615 USD/m^3.Finally equipment maintence costs were estimated at 2.2 $EUR-cent/m^3$ or about 2 to 2.5 % of plant investment costs. A study from 2004 [52] estimates MSF investment costs at about 1000 Eurs/m^3/day of capacity and about 700

Eurs/m^3/day for Reverse Osmosis processes.

$$SeawaterCost_{INV} = 7100 * C^{0.85} BrackishCost_{INV} = 1850 * C^{0.82} \tag{6.6.1}$$

Another study [38] provides the changes in the costs of desalination in recent years, shown in Table 6.7. The same study also provides a cost breakup of desalination for reverse osmosis technologies for seawater and brackish water reproduced in Table 6.8.

.

.

Table 6.7: Changes in costs of desalination plants in Spain (1995-2010)

Parameters	1995	2002	2004	2010
Investment (Eur/m3/day)	890.00	610.00	600.00	590.00
Period of Amortization (Years)	15.00	15.00	15.00	15.00
Intrest (%)	10.00	4.00	4.00	4.00
Specific Consumption (KW/h/m3)	5.30	4.10	3.60	2.90
Price of Water (Eur/KW/h)	0.08	0.05	0.05	0.05
Electric Energy	0.41	0.20	0.17	0.14
Labour	0.04	0.04	0.03	0.02
Chemical Products	0.03	0.03	0.03	0.03
Maintenence	0.02	0.02	0.02	0.02
Replacement of Membranes	0.02	0.02	0.02	0.01
Total Use (Eur/m3)	0.52	0.30	0.27	0.23
Amortization (Eur/m3)	0.34	0.17	0.17	0.16
Total Cost (Eur/m3)	0.85	0.47	0.44	0.40

Table 6.8: Changes in costs of desalination plants in Spain (1995-2010)

Parameters	Brackish Water Plants (1000-10000 m3/day)	Seawater Plants (10000-140000 m3/day)
Energy	0.030-0.080	0.140-0.176
Labour	0.017-0.035	0.014-0.100
Chemicals	0.017-0.055	0.018-0.048
Membrane	0.005-0.009	0.008-0.031

Table 6.8: Changes in costs of desalination plants in Spain (1995-2010)

Parameters	Brackish Water Plants (1000-10000 m3/day)	Seawater Plants (10000-140000 m3/day)
Consumibles	0.003-0.005	0.003-0.006
Maintenence	0.006-0.012	0.017-0.034
Total	0.078-0.196	0.2-0.395

6.7 Water Efficiency

Efficiency of desalination plants can be characterised by a water recovery factor which depends on the type of technology used and the degree of salinity of the water being processed. With higher concentrations of salts processing the waste brine becomes more challengining since the concentration of the brine increases as you increase the ratio of water recovery [42]. Some ranges of water recovery for different processes and water sources are provided in Table 6.9 [46]. Another study gives the typical recovery ratio for desalination processes as 1 to 3 [48]. Another study from 2005 [49] studies a single MSF plant with capacity $100m^3/hour$ and gives a design recovery ratio of 42%.

Table 6.9: Range of desalination water recovery parameters

Technology	Water Recovery (%)
Brackish water Reverse Osmosis	50-80
Seawater Reverse Osmosis	40-50
Electrodialysis Reversal	70-90

A study from 2001 [51] compares the performance of some typical desalination plants and the results for the energy consumption and recovery ratio are presented in Table 6.10.

Table 6.10: Range of desalination water recovery parameters

Technology	Capacity (m3/day)	Water Recovery (%)	Heat consumption (kWh/m3)	Electric consumption (kWh/m3)
Multi Stage Flash	27,300	10.51	16.72	4.2

Table 6.10: Range of desalination water recovery parameters

Technology	Capacity (m3/day)	Water Recovery (%)	Heat consumption (kWh/m3)	Electric consumption (kWh/m3)
Multi Stage Flash	32,700	13.44	15.32	3.68
Multi effect distillation	10,000	14.44	13.65	1.8
Mechanical Vapour Compression	700	41.67	-	12.0
Mechanical Vapour Compression	1500	41.67	-	11.5
Mechanical Vapour Compression	3000	48.08	-	11.0
Reverse Osmosis Brackish Water	Variable	53	-	2.1
Reverse Osmosis Seawater (ER)	600	34.24	-	5.1
Reverse Osmosis Seawater (no ER)	600	34.24	-	6.4

6.8 Existing Capacity

According to one study [42] which cites the International Desalination Association, in 2008 Spain had an installed desalination capacity of 5.428 million m^3/day accounting for 9 % of global production capacity. This ranked Spain at fourth in desalination capacity after the Saudi Arabia, United Arab Emirates and the United States of America.

The distribution of desalination capacity in 2010 by autonomous communities [38] is provided in Table 6.11. Table 6.12 from the same study [38] provides additional desalination projects being developed for 2012 at the time.

Table 6.11: Desalination plants in Spain 2010

Autonomous Community	Capacity(m3/day)	No. Instalations
Andalucia	816,658	67
Comunidad Valenciana	714,080	87
Canarias	671,602	317
Murcia	454,698	71
Cataluna	381,776	83
Baleares	189,146	30
Castilla la Mancha	97,936	32
Ceuta y Melilla	43,000	3

Table 6.11: Desalination plants in Spain 2010

Autonomous Community	Capacity(m3/day)	No. Instalations
Aragon	40,609	10
Castilla-Leon	9,448	18
Extremadura	2,700	3
Asturias	1,000	1
Navarra	960	1
Madrid	800	7
Galicia	752	2
La Rioja	720	1
Pais Vasco	616	3
Cantabria	340	2
Totals	3,426,841	738

Table 6.12: Additional desalination plants planned for 2012

Autonomous Community	Capacity(m3/day)
Canarias	87,500
Baleares	25,000
Andalucia	192,000
Murcia	210,000
Comunidad Valencia	411,800
Cataluna	4e+05
Totals	1,326,300

The data from the Spanish Ministry of the environment gives a spreadsheet with the distribution of desalination capacity per county in Spain [44]. This county GIS map was overlayed with the river boundaries and the desalination capacity in each river basin was then aggregated accordingly. The distribution of desalination technologies in different river basins determined using this methodology is shown in Table 6.2 above.

6.9 Future Predictions and Climate Change

Chapter 7

Water Purification and Reuse

7.1 Key Points & Assumptions

Key Points

- Water needs to be treated to protect human health and environmental degradation.
- Most developed countries already require costly treatment of wastewater. Not reusing it is wasting it.
- Most developing countries often lack infrastructure to capture and treat wastewater.
- Most developing countries lack water quality regulations or checks and reuse wastewater without treatment causing health concerns.
- Treated municipal wastewater is steady in volume, its quality is regulated and is close to urban users
- Treated wastewater can be of a higher quality than raw freshwater and can be used for almost any purpose (Although most countries still forbid direct potable use of reclaimed water)

Key Assumptions

- Freshwater is treated by treatment plants for urban/municipal water supply and services
- Direct use of treated/reclaimed municipal wastewater requires separate piplines to be layed to each user

- Freshwater used by industries and the waste water produced is directly treated by industries themselves
- Agriculture users directly use untreated freshwater and produce untreated wastewater runoff

7.2 Parameter Summary

Water qualities are categorized as follows (letters A to F correspond to quality levels detailed in Table 7.7):

Water Quality

- Freshwater Untreated - FWU
- Treated Freshwater - FWA, FWB, FWC, FWD, FWE
- Wastewater Untreated- WWU
- Treated Wastewater - WWA, WWB, WWC, WWD, WWE
- Water Consumed (Evapotranspiration) - WET
- Ocean(Salt) Water - SW

Next, treatment of freshwater and wastewater can involve the same processes and even the same plants, however the water itself is managed in separate pipes. Therefore a distinction is made between purification (pur) of freshwater processes and recycling (rcyl) of wastewater processes. Each purification and recycling process is defined by a group of treatment trains detailed in Table 7.8. Each treatment train delivers a particular quality of water which is suitable for different uses as listed by regulation in Table 7.7. The for each train the corresponding treatment train, operation costs, investment costs, energy consumption and water losses are listed in Table 7.1 and Table 7.2

Table 7.1: Purification process parameters used in model

Purification Processes (pur)	Water Quality out	Treat-ment Train	Investment cost p_cost_pur_Inv(pur) (€/(m^3/day))	Operation cost p_cost_pur_OnM(pur) (€/m^3)	Energy consumption p_nrg_pur(pur) (kWh/m^3)	Water Loss % p_wloss_pur(pur) (%)
purFW4toE	E	4	8	0.04	0.12	0
purFW3toCD	CD	3	15	0.04	0.67	0
purFW2toB	B	2	37	0.06	0.67	0
purFW1toA	A	1	257	0.13	0.67	4
purFW5btoBCDE	BCDE	5b	327	0.3	5.67	20
purFW5atoABCDEF	ABCDEF	5a	359	0.3	5.67	34

Notes:
1:Life time is assumed to be 20 years for all the treatment trains.
2: Interest rate is assumed to be 4% for all the treatment trains.

Table 7.2: Wastewater Recyling process parameters used in model

Purification Processes (rcyl)	Water Quality out	Treat-ment Train	Investment cost p_cost_rcyl_Inv(rcyl) (€/(m^3/day))	Operation cost p_cost_rcyl_OnM(rcyl) (€/m^3)	Energy consumption p_nrg_rcyl(rcyl) (kWh/m^3)	Water Loss % p_wloss_rcyl(rcyl) (%)
rcylWW4toE	E	4	8	0.04	0.12	0
rcylWW3toCD	CD	3	15	0.04	0.67	0

rcylWW2toB	B	2	37	0.06	0.67	0
rcylWW1toA	A	1	257	0.13	0.67	4
rcylWW5btoBCDE	BCDE	5b	327	0.3	5.67	20
rcylWW5atoABCDEF	ABCDEF	5a	359	0.3	5.67	34

Notes:

1:Life time is assumed to be 20 years for all the treatment trains.

2: Interest rate is assumed to be 4% for all the treatment trains.

The distribution of existing capacity by basin is given in Table 7.18 where the water purification processes are grouped by treatment options. This total capacity (7910 hm^3) is several times the amount of water currently purified (3181hm^3) and much more than the amount of reclaimed water reutilized (about 430hm^3).

7.3 Worked Example

In Figure 7.1 we have a basic example of a possible purification scenario. We make the following initial assumptions:

Initial Assumptions for a single Month

- Urban demand for Freshwater Quality A = 250 hm^3
- Agriculture demand for untreated freshwater or treated Wastewater B = 750 hm^3
- Freshwater available in Basin = 950 hm^3
- Existing purification Capacity = 186 hm^3

Using the parameters from Section 7.2 we make the following Investment calculations:

Additional Capacity

- Additional purification capacity needed: 260 - 186 = 74 $hm^3/month$
- Additional capacity needed in m^3/day = (74 × 1000,000 m^3/hm^3) / (30 $days/month$) = 246,667 m^3/day
- Total Investment (€)) = p_cost_pur_Inv(FWA) × Capacity needed = 257 × 246,667 = €633,933,333
- Annuity = Principal $\times(i + i/((1+i)^n - 1))$ = 633,933,333 $\times(0.04 + 0.04/((1.04)^n - 1))$ = €46,645,924

Once the additional capacity has been installed we can investigate the operation of two cases as shown in Figure 7.1. In Case 2, we assume that the pipelines required to carry reclaimed water to the agriculture reuse site are already installed. Of course, as seen in the example, there is no additional cost for the preparation of reclaimed water and the main barrier to its actual reuse is the laying of reclaimed water pipelines and delivering it to the appropriae users. This will be explored further in the section on distribution and water transfers. In the current example, by recycling water we are able to avoid the costs of unsupplied water to the agriculture sector.

Operation and Maintenence Case 1

- Freshwater Purification A in = 260 hm^3
- Freshwater Purification A lost = 260 × 4% = 10 hm^3
- Freshwater Purification A through = 250 hm^3
- Freshwater Purification A Energy = 260 × 0.67 = 174.2 GWh
- Freshwater Purification A OnM Cost = 260 × 0.13 = 33.8 M€
- Urban Freshwater A Demand in = 250 hm^3
- Urban Freshwater A Demand lost (assume 1/5th) = 250/5 = 50 hm^3
- Urban Freshwater A Demand through = 200 hm^3
- Municipal Wastewater B in (assume aglomeration > 10000) = 200 hm^3
- Municipal Wastewater B lost = 0 hm^3
- Municipal Wastewater B through = 200 hm^3
- Municipal Wastewater B Energy = 200 × 0.67 = 134 GWh
- Municipal Wastewater B OnM Cost = 260 × 0.06 = 12 M€
- Agriculture Freshwater Untreated in = 690 hm^3
- Agriculture Freshwater Untreated lost (assume 1/5th) = 690/5 = 138 hm^3
- Agriculture Freshwater Untreated through = 690-138 = 552 hm^3
- Agriculture Freshwater Untreated Unmet = 750 - 690 = 60 hm^3
- Total water treated = 260 + 200 = 460 hm^3
- Total water purification Energy = 174.2 + 134 = 308.2 GWh
- Total water purification OnM Cost = 33.8 + 12 = 45.8 M€

Case 2 is exactly the same uptill the municipal wastewater treatment plant. The following changes are made after this point.

Operation and Maintenence Case 2

- Municipal Wastewater B in (assume aglomeration > 10000) = 200 hm^3

- Municipal Wastewater B lost = 0 hm^3
- Municipal Wastewater B recycled = 60 hm^3
- Municipal Wastewater B through = 200 hm^3
- Municipal Wastewater B Energy = 200 × 0.67 = 134 GWh
- Municipal Wastewater B OnM Cost = 260 × 0.06 = 12 M€
- Agriculture Freshwater Untreated in = 690 hm^3
- Agriculture Wastewater B in = 60 hm^3
- Agriculture Water lost (assume 1/5th) = (690 + 60)/5 = 150 hm^3
- Agriculture Water Untreated through = 750 - 150 = 600 hm^3
- Agriculture Water Untreated Unmet = 750 - 750 = 0 hm^3
- Total water treated = 260 + 200 = 460 hm^3
- Total water purification Energy = 174.2 + 134 = 308.2 GWh
- Total water purification OnM Cost = 33.8 + 12 = 45.8 M€

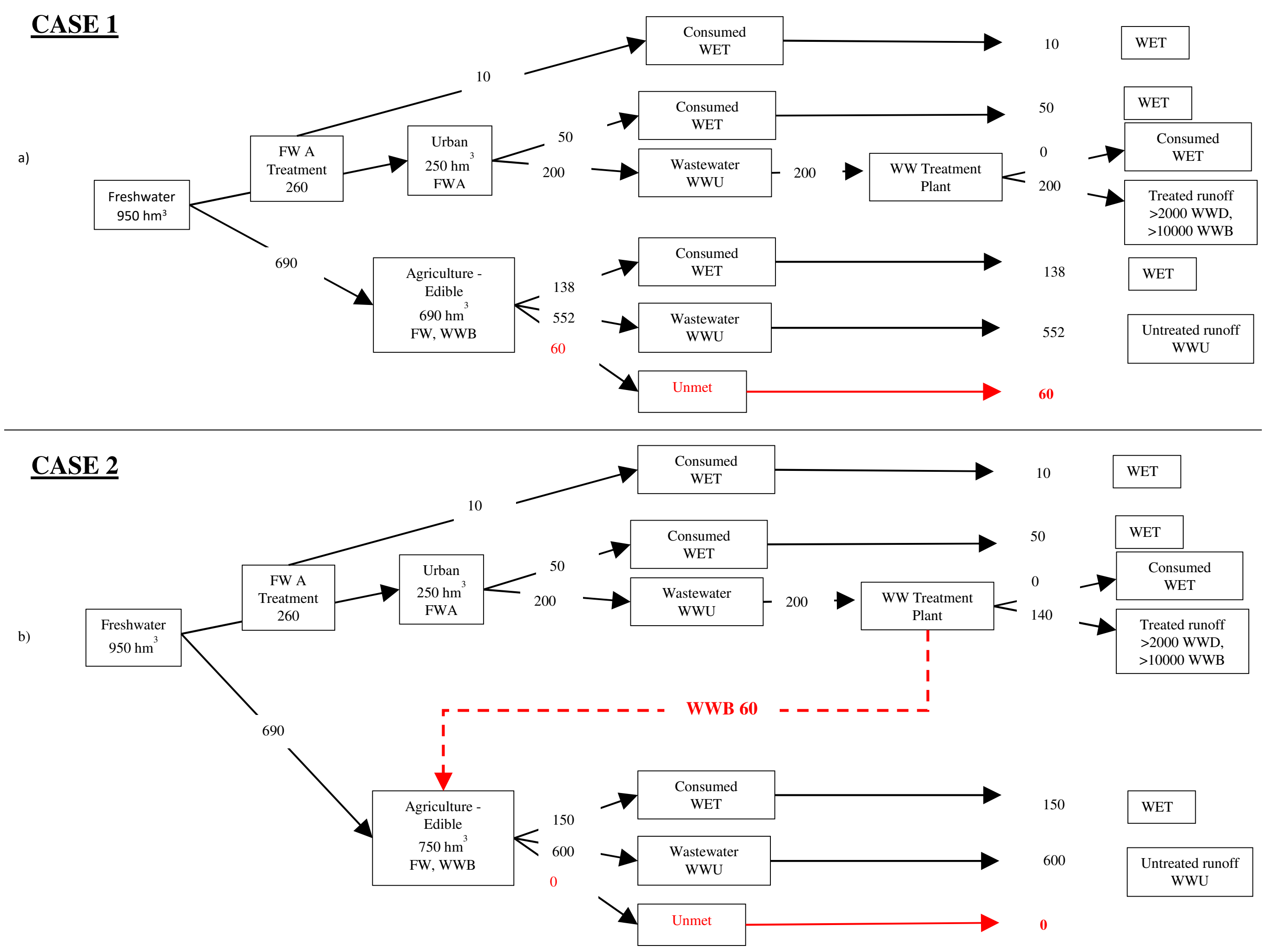

Figure 7.1: Worked example for purification and wastewater treatment flows

7.4 Introduction

Several studies [53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63] not directly cited in this paper were used to analyze and understand the situation of water reuse and purification globally and locally in Spain. The following paragraphs discuss breifly the key issues of water treatment, where it comes from, quality definitions, who produces it and how it is regulated.

Jimenez (2008) [64] gives a summary of the global leaders in water reuse using three different criteria. The top ten entries from the original table are reproduced in Table 7.3. Not shown in the table, Spain was ranked eighteen in reuse m^3/d per million capita with $20,436$ and ranked 23 in reuse/extraction % with 0.8.

In areas with increasing pressures on water resources and where existing resources are already or nearing overcommittement "society no longer has the luxury of using water only once" [65]. Water reuse has several benefits including: Substituting reclaimed water in applications not requiring high-quality potable water; augmenting existing sources; protecting aquatic ecosystems by preventing diversion of freshwater; protecting aquatic ecosystems by decreasing amount of pollutants and toxic contaminants entering waterways; reducing need for water control structures such as dams and reservoirs; and complying with environmental regulations by better managing consumption and wastewater discharges. The main drivers for resusing water in both developed and developing countries are: lack of water; drought management; to ensure a reliable source of water; generation of wastewater near agricultura fields demanding water; and high demand in local areas for urban and industrial purposes [64]. Other drivers are: proximity of reclaimed municipal wastewater to urban centers; dependability since urban waste water remains nearly constant; versatility to be processed to qualities required; safe quality with testing; economic and environmental benefits; increasing public awareness; more stringent regulations; and necessity [65].

Wastewater is produced by all sectors using water however, the most reliable and significant source for reclaimed water is municipal sewage from urban centers [65]. These urban centers provide a concentrated source of wastewater, which makes it easier to install the necessary infrastructure. Agriculture and industries located away from urban centers need to comply with regulations before disposing of their waste water to other water sources. As an example in Canada, manufacturing industries discharged 75% of their wastewater to surface freshwater bodies, 11% to tidewater and 10% to public and municipal sewers. The remainder went to groundwater or other points. 38% of the discharge was not treated before being released. Mining industries discharged 73% of their wastewater to surface freshwater, while discharging another 11% to tailing ponds and 9% to groundwater. Thermal-electric power generation industries discharged 95% of their wastewater to surface freshwater bodies 59% of which was not treated [66].

Municipal wastwater or sewage can come from a variety of different sources (households, schools, offices, hospitals and commercial facilities) with a variety of different possible biological and chemical contaminants. Crops and vegetables grown with untreated contaminated water are a major source of enteric disease. A summary of some of the common constituents found in wastewater are shown in Table 7.4 [65].

After being treated, reclaimed water can be used for agricultural irrigation (Crop irrigation, commercial nurseries), landscape irrigation (Parks, School yards, freeway medians, golf courses, cemeteries, greenbelts, residential), industrial recycling and reuse (Cooling water, boiler feed, process water, heavy construction), groundwater recharge (Groundwater replenishment, salt water intrusion control, subsidence control), recreational uses (Lakes and ponds, marsh enhancement, streamflow augmentation, fisheries, snowmaking), nonpotable urban uses (Fire protection, air conditioning, toilet flushing) and potable reuse (Blending in water supply reservoirs, blending in groundwater, direct pipe to pipe water supply) [65].

In most developed countries, for each type of reuse, the quality of water must be ensured by according to regulations. There are several different treatment options available which can be used in differnt combinations corresponding to the desired results and quality standards. Different processes are categorized into preliminary, primary, secondary, tertiary or advanced methods, however, the categorization varies amongst studies. A good summary of the processes available and how they may be used in sequence is shown in Figure 7.3 [65]. Of course, not all the processes are used in one treatment and only a selction of those available are chosen. The different processes can be categorized broadly as follows:

Water Treatment Processes

i Preliminary: Removal of wastewater constituents such as rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems.

ii Primary: Remove gross, suspended and floating solids from raw sewage. It includes screening to trap solid objects and sedimentation by gravity to remove suspended solids. Chemicals are often used to accelerate the sedimentation process. Primary treatment can reduce the BOD of the incoming wastewater by 20-30% and the total suspended solids by some 50-60%.

iii Secondary: Removes the dissolved organic matter that escapes primary treatment.

This is achieved by microbes consuming the organic matter as food, and converting it to carbon dioxide, water, and energy for their own growth and reproduction. The biological process is then followed by additional settling tanks to remove more of the suspended solids. About 85% of the suspended solids and BOD can be removed.

iv Nutrient Removal (Secondary or Tertiary): Removal of nutrients such as Nitrogen and Phosphorous

v Tertiary: Removes more than 99 percent of all the impurities from sewage, producing an effluent of almost drinking-water quality. The related technology can be very expensive, requiring a high level of technical know-how and well trained treatment plant operators, a steady energy supply, and chemicals and specific equipment which may not be readily available. An example of a typical tertiary treatment process is the modification of a conventional secondary treatment plant to remove additional phosphorus and nitrogen.

vi Disinfection: Typically with chlorine, can be the final step before discharge of the effluent. However, some environmental authorities are concerned that chlorine residuals in the effluent can be a problem in their own right, and have moved away from this process. Disinfection is frequently built into treatment plant design, but not effectively practiced, because of the high cost of chlorine, or the reduced effectiveness of ultraviolet radiation where the water is not sufficiently clear or free of particles. Sometimes residual chlorine in the water is used to control biofilm growth in distribution system.

A summary of the processes available and their categorization is shown in Table 7.5. Table 7.6 [65] shows some examples of the prescence of different wastewater constituents (from Table 7.5) in untreated municipal sewage and the effectivenes of different treatment process combinations (from Figure 7.3 and Table 7.5)

Table 7.3: Leading countries in water reuse [64]

Rank	Country	Total reuse m^3/d	Country	Reuse m^3/d per million capita	Country	Reuse/Extraction %
1	China	14,817,000	Qatar	170,323	Kuwait	35.2
2	Mexico	14,400,000	Israel	166,230	Israel	18.1
3	USA	7,600,000	Kuwait	163,330	Singapore	14.4
4	Egypt	1,920,000	Mexico	136,235	Qatar	13.3

Table 7.3: Leading countries in water reuse [64]

Rank	Country	Total reuse m^3/d	Country	Reuse m^3/d per million capita	Country	Reuse/Extraction %
5	Saudi Arabia	1,847,000	UAE	126,713	Cyprus	10.4
6	Syria	1,014,000	Cyprus	88,952	Jordan	8.1
7	Israel	1,014,000	Saudi Arabia	75,081	UAE	8
8	Chile	840,600	Bahrain	56,301	Malta	7.8
9	Spain	821,920	Syria	55,109	Tunisia	7.1
10	Japan	573,800	Chile	52,211	Mexico	6.7

Table 7.4: Constituents of wastewater [65]

Constituents	Examples	Descriptions	Problems
Biological			
Bacteria			
(Colony Forming Units (CFU)/100mL)	Escherichia Coli (E.coli), Legionella, Shigella, Salmonella,Yersinia enterocolitica, Campylobacter jejuni	Bacteria are microscopic organizms between 0.2 to 10 micrometers in length. Pathogenic enteric (of intestines) bacteria can be transmitted to humans through fecal-oral routes.	Diarrhea, dysentery, typhoid, cholera
Protozoa			
(No./100 mL)	Giardia Lamblia, Cryptosporidium parvum, Entamoeba histolytica	Protozoa are single-celled organisms typically larger than bacteria. Enteric protozoan parasites produce cycts or oocycts that aid in their survival.	Diarrhea, fatigue, cramps,
Helminths			

Table 7.4: Constituents of wastewater [65]

Constituents	Examples	Descriptions	Problems
(eggs/10L)	Intestinal Nematodes, Taenia saginata, Taenia Solium, Ascaris lumbricoides, Schistosoma mansoni	Helminths are a group of parasitic worms, when large can be seen with the naked eye. Transmitted by ingestion of contaminated salads and vegetables, and by worms inhabiting veins in the host penetrating through the skin.	Principal causative agent of human disease globally, causing about 4.5 billion illnesses a year. Abdominal pains, vomiting, liver, urinary issues.
Viruses			
(Plaque forming Units (PFU/100 mL))	Hepatitis A, Rotavirus, Noroviruses, Caliciviruses, Enterovirus	Viruses are intracellular parasites, 0.01 to 0.3 micro meters in size, only able to multiply within a host cell. Most common way of transmission is through drinking water.	Gastroenteritis, respiratory infections, encephalitis, neonatal disease, myocarditis, aseptic meningitis, jaundice
Chemical			
Organic Matter			

Table 7.4: Constituents of wastewater [65]

Constituents	Examples	Descriptions	Problems
(Biochemical Oxygen Demand (BOD) mg/L - Chemical Oxygen Demand (COD) mg/L - Total Organic Carbon (TOC) mg/L)	Biodegradable organics, Surfacants, phenols, agricultural pesticides	Biodegradable organics provide food for microorganisms and are composed of proteins, carbohydrates and fats.	Carcinogenicity, mutagenicity, teratogenicity, high acute toxicity, adeversly affect disinfection processes, make water unsuitable for some industrial processes
Inorganic Matter (mg/L)	Calcium, sodium, sulfate, heavy metals (cadmium, copper, molybdenum, nickel, zinc)	Inorganic chemcial constituents including heavy metals	Heavy metal accumalations in crops can be toxic to consumers
Nutrients (mg N/L , mg P/L)	Nitrogen, Phosphorous	Nitrogen and Phosphorous in various forms	Nitrates in excess can leech through soil and cause groundwater concentrations to exceed drinkning water standards. Stimulate undesierable growth of undesirable aquatic life.
Trace constituents			

Table 7.4: Constituents of wastewater [65]

Constituents	Examples	Descriptions	Problems
(mg/L)	Phamaceutically active comounds (PhACs), endocrine disruppting compounds (EDCs), personal care products, etc.	Pesticides, pharamceuticals, hormonolly active agents, residual personal care products	Adverse effects to frogs, fish and other aquatic animals, unknown health risks
Hydrogen ion concentration - pH			
pH scale (0-14)	H+ ion in acids	Hydrogen ion concentration gives the pH level of the water	Affects disinfection efficiency, coagulation, metal solubility, alkalinity of soils, other chemical treatment processes
Disinfection byproducts (DBPs)			
(mg/L)	Trihalomethanes, haloacetic acids, bromate, haloacetonitriles	Formed during the reaction of chemical oxidants such as chlorine and ozone with organics in water	Harmful to human health if ingested over long time
Total dissolved solids (TDS)			
(mg/L)	Dissolved organic and inorganic matter	Dissolved organic and inorganic matter	Affect suitability of reclaimed water for industrial reuse, agricultural irrigation, groundwater recharge

Table 7.4: Constituents of wastewater [65]

Constituents	Examples	Descriptions	Problems
Physical			
Total suspended solids (TSS) (mg/L)	Organic and inorganic suspended solids	Suspended solids	Shields microorganisms from disinfectants and react with disinfectants such as cholrine or ozone to decrease effectiveness
Turbidity (Nephelometric Turbidity Units (NTU))	Suspended particles in fluid	Haziness of fluid caused by suspended particles. Turbidity can be used as a surrogate measure of suspended solids however it cannot give the particle size distribution. Measured using light dispersion with a nephelometer	Shields microorganisms from disinfectants and react with disinfectants such as cholrine or ozone to decrease effectiveness
Temperature			

Table 7.4: Constituents of wastewater [65]

Constituents	Examples	Descriptions	Problems
(Degrees celcius or Farenhite)	Temperature	Wastewater temperature is usually higher than ambient environment temperature	Affects certain reuse application such as cooling, causes accelerated biological growth, scaling in pipes and appurtenances
Other physical properties (Various units)	Odor, Transmittace, conductivity	Other physical properties may be of concern depending on the particular use	Depends on use

Figure 7.2

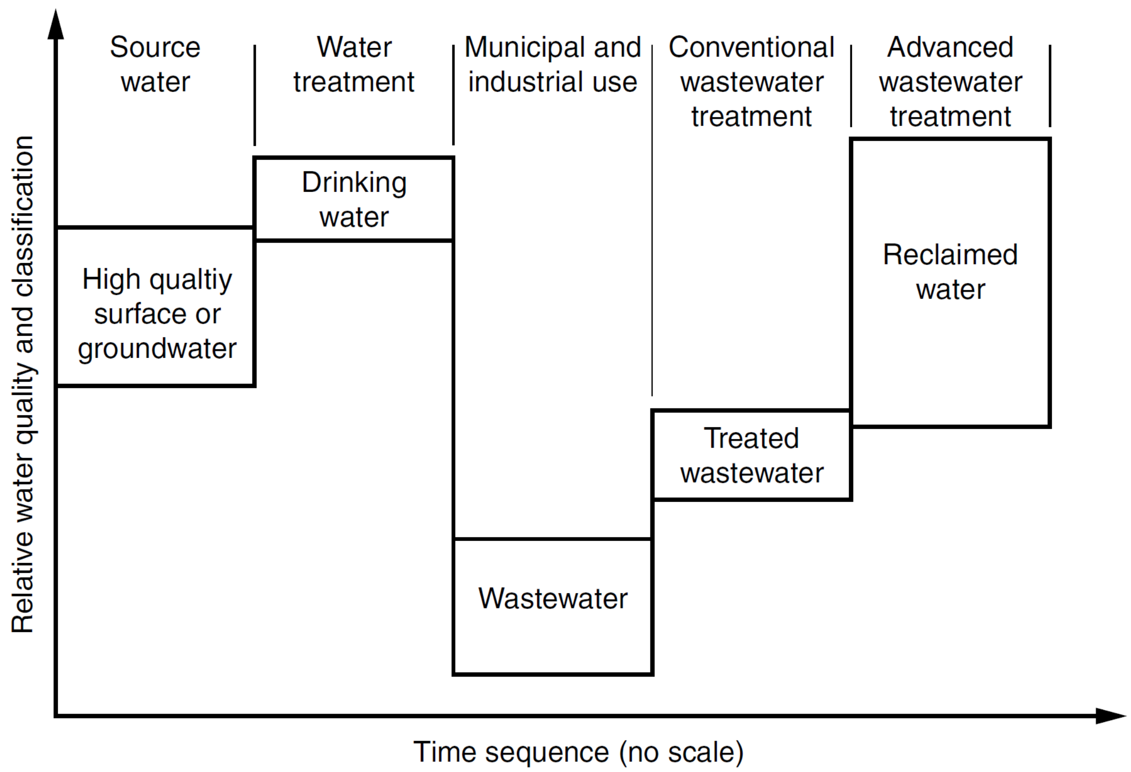

Figure 7.2: Water quality changes during municipal reuse (from Asano 2007 [65])

Table 7.5: Wastewater treatment processes [65]

Treatment Level	Treatment sub-level	Process Examples
Preliminary	Preliminary	Bar Screen, Grit Chamber
Primary	Primary	Clarification, Fine Screen
Secondary	Secondary	Membrane bioreactor, Activated sludge, Trickling filters, Rotating biological contactors
Secondary or Tertiary (Nutrient Removal)	Nitrogen removal	Biological Nitrogen Removal (BNR)
	Phosphorous removal	Chemical precipitation phosphorous removal, Biological phosphorous removal

Table 7.5: Wastewater treatment processes [65]

Treatment Level	Treatment sub-level	Process Examples
Tertiary or Advanced	Residual Suspended solids removal	Microfiltration, Depth filtration, Surface filtration, Dissolved air flotation
	Residual colloidal solids removal	Microfiltration, Ultrafiltration
	Residual dissolved solids removal	Nanofiltration, Reverse Osmosis, Electrodialysis
	Residual and specific trace constituent removal	Advanced oxidation, Carbon adsorption, Ion exchange,
Disinfection	Disinfection	Chlorination, residual chlorine, Ultaviolet (UV) radiation, Ozone

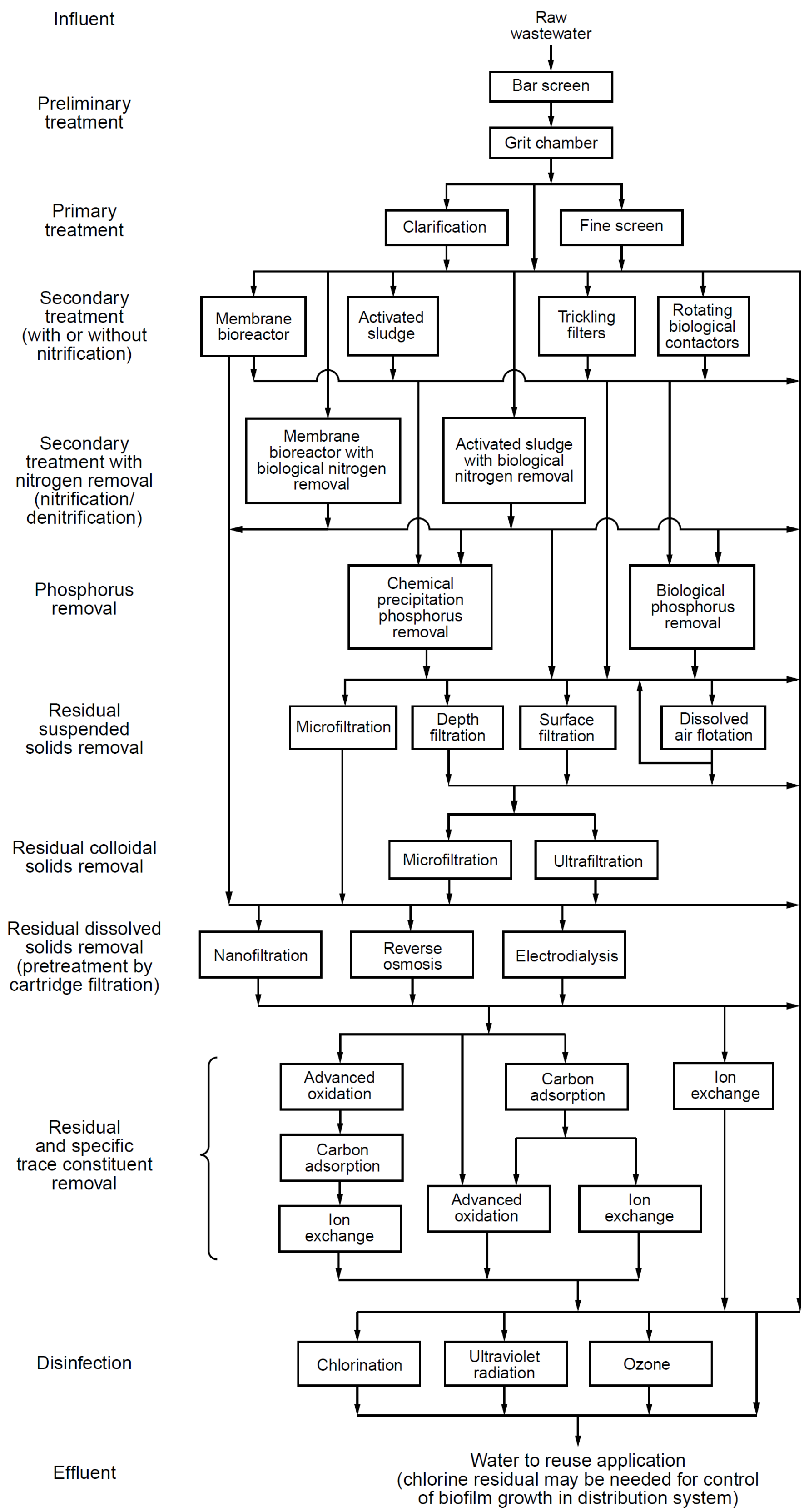

Figure 7.3: Water treatment processes (from Asano 2007 [65])

Table 7.6: Wastewater constituents and treatment process effectiveness [65]

Constituent Category	Constituent	Unit	Untreated Wastewater	Conventional activated sludge	Conventional activated sludge with flitration	Activated sludge with BNR (Biological nutrient removal for phosphorous and nitrogen)	Activated sludge with BNR and filtration	Membrane bioreactor	Activated sludge with microfiltration and reverse osmosis
Biological (Bacteria)	Total coliform	No./100 mL	106-109	104-105	103-105	104-105	104-105	<100	~0
Biological (Protozoa)	Protozoan cysts and oocysts	No./100 mL	101-104	101-102	0-10	0-10	0-1	0-1	~0
Biological (Virus)	Viruses	PFU/100 mL	101-104	101-103	101-103	101-103	101-103	100-103	~0
Chemical (Organic)	Biochemical Oxygen Demand (BOD)	mg/L	110-350	5-25	<5-20	5-15	1-5	<1-5	≤1
Chemical (Organic)	Chemical Oxygen Demand(COD)	mg/L	250-800	40-80	30-70	20-40	20-30	<10-30	≤2-10

Table 7.6: Wastewater constituents and treatment process effectiveness [65]

Constituent Category	Constituent	Unit	Untreated Wastewater	Conventional activated sludge	Conventional activated sludge with flitration	Activated sludge with BNR (Biological nutrient removal for phosphorous and nitrogen)	Activated sludge with BNR and filtration	Membrane bioreactor	Activated sludge with microfiltration and reverse osmosis
Chemical (Organic)	Total Organic Carbon (TOC)	mg/L	80-260	10-40	8-30	8-20	1-5	0.5-5	0.1-1
Chemical (Organic)	Volatile Organic Compounds (VOCS)	μg/L	100-400	10-40	10-40	10-20	10-20	10-20	≤1
Chemical (Organic)	Surfactants	mg/L	4-10	0.5-2	0.5-1.5	0.1-1	0.1-1	0.1-0.5	≤1?
Chemical (Nutrients, Nitrogen)	Ammonia nitrogen	mg N/L	12-45	1-10	1-6	1-3	1-2	<1-5	≤0.1

Table 7.6: Wastewater constituents and treatment process effectiveness [65]

Constituent Category	Constituent	Unit	Untreated Wastewater	Conventional activated sludge	Conventional activated sludge with flitration	Activated sludge with BNR (Biological nutrient removal for phosphorous and nitrogen)	Activated sludge with BNR and filtration	Membrane bioreactor	Activated sludge with microfiltration and reverse osmosis
Chemical (Nutrients, Nitrogen)	Nitrate nitrogen	mg N/L	0-trace	10-30	10-30	2-8	1-5	<10	≤1
Chemical (Nutrients, Nitrogen)	Nitrite nitrogen	mg N/L	0-trace	0-trace	0-trace	0-trace	0-trace	0-trace	0-trace
Chemical (Nutrients, Nitrogen)	Total nitrogen	mg N/L	20-70	15-35	15-35	3-8	2-5	<10	≤1
Chemical (Nutrients, Phosphorous)	Total phosphorus	mg P/L	4-12	4-10	4-8	1-2	≤2	<0.3e-5	≤0.5
Chemical	Metals	mg/L	1.5-2.5	1-1.5	1-1.4	1-1.5	1-1.5	trace	≤?

Table 7.6: Wastewater constituents and treatment process effectiveness [65]

Constituent Category	Constituent	Unit	Untreated Wastewater	Conventional activated sludge	Conventional activated sludge with flitration	Activated sludge with BNR (Biological nutrient removal for phosphorous and nitrogen)	Activated sludge with BNR and filtration	Membrane bioreactor	Activated sludge with microfiltration and reverse osmosis
Chemical	Totals dissolved solids (TDS)	mg/L	270-860	500-700	500-700	500-700	500-700	500-700	≤5-40
Chemical	Trace constituents	μg/L	10-50	5-40	5-30	5-30	5-30	0.5-20	≤0.1
Physical	Total Suspended Solids (TSS)	mg/L	120-400	5-25	2-8	5-20	1-4	≤2	≤1
Physical	Colloidal Solids	mg/L		5-25	5-20	5-10	1-5	≤1	≤1
Physical	Turbidity	NTU		2-15	0.5-4	2-8	0.3-2	≤1	0.01-1

7.5 Regulations

In order to decide which watertreatment technologies to use it is necessary to establish what quality of water is required for different purposes. Iglesias Esteban (2008) provides a review of the different regulations [67] with regards to water reuse in Spain. A summary of the main developments are provided below:

Key developments in the Spanish water treatment regulations

- Reclaimed water regulation started since 1970's with partial plans in some coastal tourist areas
- Main push to regulate came after the European Community Directive 91/271/EEC (21 May 1991) on urban wasstewater. The key points put forward were:
  - i Collection and treatment of wastewater in all agglomerations of >2000 inhabitants
  - ii Secondary treatment of all discharges from agglomeration of >2000 inhabitants
  - iii Advanced treatment in agglomertions >10000 and designated sensitive areas
  - iv Pre-authorization of all disharges into urban wastewater systems
  - v Monitroing of performance of treatment plants and receiving waters
  - vi Controls of sewage sludge disposal and re-use
  - vii Treated wastewater reuse when possible
- After the European directive regulations applied via Spanish Law via Act 11/1995 and Royal Decree 509/1996.
- The National Sewerage and Treatment Plan (PNSD) 1995 proposed to build infrastructure till 2005 as part of the 10 year plan. The strategies had a 11.4 M€budget and 70 million people were affected living in agglomerations >2000 in December 2004
- Water reuse was officially regulated in the Water Act 1995 which specifies that reuse requires a license from the authorities and that the government will establish the quality required for treated water for different uses.
- In 1996, the Ministry of Environment (MMA) put forth the first draft of regulations which were approved by the Council of State however with some debate.
- In 1999 a project was established by Royal Decree and had broad consensus on a technical and political level. The main promoters were the Spanish Supply and Sewerage

Association (AEAS) and CEDEX. The points were adopted in regulations of the Autonomous regions of Cataluna and Baleares and in some water authorities in Tajo. Were not a legal regulation but became the basis for regulations at other levels.

– In 2007, the Royal Decreee 1620/2007 [68] clearly stated the official quality requirements for the use of reclaimed water in for different purposes. these have been adopted in the National Plan for Reutilization of Water in Spain [69] in which different treatment process options are also recommended. The regulated qualities for different users and corresponding treatment options are summarized in Table 7.7.

Recalimed water is explicitlly forbidden for human consumption (except in the state of an emergency), for use in the food industry, hospitals and similar facilities, bivalve mollusk aquaculture facilities, for swimming water in recreational facilities, cooling ad evaporative towers (expect for industrial uses, quality 3.2 not located close to urban areas), ornamental fountains and water surfaces in outdoor and indoor public spaces and any other use considered as a public or environmental health risk by the authorities.

The National Plan for Reutilization of Water in Spain [69] suggests different treatment trains options for different sectors and uses as shown in Table 7.7. These treatment trains as defined in the National Plan are presented in Table 7.8 with details on the types of processes involved in each train. The costs, energy consumption and efficiency of each train are then discussed in later sections.

Table 7.7: Spanish water reuse regulations and treatment process options [69]

Sector	Use	Use Code	Quality	Treatment Train	Intestinal Nematodes (egg/10 L)	E.coli (CFU/ 100 mL)	Suspended Solids (mg/L)	Turbidity (NTU)	Legionella (CFU/L)
Urban - Residential	Irrigation of private gardens	1.1a	A	1,5a	1	0	10	2	100
Urban - Residential	Supply to sanitary appliances	1.1b	A	1,5a	1	0	10	2	100
Urban - Services	Landscape irrigation of urban areas	1.2a	B	2,5b	1	200	20	10	100
Urban - Services	Street cleansing	1.2b	B	2,5b	1	200	20	10	100
Urban - Services	Fire hydrants	1.2c	B	2,5b	1	200	20	10	100
Urban - Services	Industrial washing of vehicles	1.2d	B	2,5b	1	200	20	10	100
Agriculture - Edible	Irrigation of edible crops to be eaten raw	2.1a	B	2,5b	1	100	20	10	1000
Agriculture - Edible	Irrigation of edible crops to be processed	2.2a	C	3,5b	1	1000	35	No limit	-
Agriculture - Edible	Irrigation of pasture lands for milk or meat producing animals	2.2b	C	3,5b	1	1000	35	No limit	-

Table 7.7: Spanish water reuse regulations and treatment process options [69]

Sector	Use	Use Code	Quality	Treatment Train	Intestinal Nematodes (egg/10 L)	E.coli (CFU/ 100 mL)	Suspended Solids (mg/L)	Turbidity (NTU)	Legionella (CFU/L)
Agriculture - Edible	Aquaculture	2.2c	C	3,5b	1	1000	35	No limit	-
Agriculture - Crops	Irrigation of tree crops no contact with fruits	2.3a	D	3,5b	1	10000	35	No limit	100
Agriculture - Crops	Irrigation of ornamental flowers, nurseries and greenhouses, no contact with crops	2.3b	D	3,5b	1	10000	35	No limit	100
Agriculture - Crops	Irrigation of industrial non-food crops, nurseries, silo fodder, cereals and oilseeds	2.3c	D	3,5b	1	10000	35	No limit	100
Industry - Process	Process and cleaning water except for food	3.1a	D	3,5b	No limit	10000	35	15	100
Industry - Process	Other industrial uses	3.1b	D	3,5b	No limit	10000	35	15	100
Industry - Process	Process and cleaning water for food industry	3.1c	C	3,5b	1	1000	35	15	100

Table 7.7: Spanish water reuse regulations and treatment process options [69]

Sector	Use	Use Code	Quality	Treatment Train	Intestinal Nematodes (egg/10 L)	E.coli (CFU/ 100 mL)	Suspended Solids (mg/L)	Turbidity (NTU)	Legionella (CFU/L)
Industry - Cooling	Cooling towers and evaporative condensers	3.2a	A	1,5a	1	Absence	5	1	Absence
Recreational - Golf	Golf course iriigation	4.1a	B	2,5b	1	200	20	10	100
Recreational - Ornamental Non Public	Ornamental ponds and lakes with no public access	4.2a	D	3,5b	No limit	10000	35	No limit	-
Environmental - Aquifer Percolation	Aquifer recharge by localized percolation through the ground	5.1a	C	3,5b	No limit	1000	35	No Limit	-
Environmental - Aquifer Direct	Aquifer recharge by direct injection	5.2a	A	1,5a	1	0	10	2	-
Environmental - Irrigation Non Public	Irrigation of woodland, green areas with no public access	5.3a	E	4,5b	No limit	No limit	35	No limit	-
Environmental - Silviculture	Silviculture	5.3b	E	4,5b	No limit	No limit	35	No limit	-

Table 7.7: Spanish water reuse regulations and treatment process options [69]

Sector	Use	Use Code	Quality	Treatment Train	Intestinal Nematodes (egg/10 L)	E.coli (CFU/ 100 mL)	Suspended Solids (mg/L)	Turbidity (NTU)	Legionella (CFU/L)
Environmental - Wetlands Streams	Wetlands, minimum stream flows and similar	5.4a	F	5a					

Table 7.8: Treatment process options from Spanish National Reutilization Plan [69]

Treatment Train	Quality	Treatment Category	(Primary) Filtration	(Secondary) Chemical Precipitation	(Tertiary) Depth Filtration	(Tertiary) Ultra Filtration	(Tertiary) EDR Desalination	(Tertiary) RO desalination	(Secondary) Disinfection UV	(Secondary) Disinfection Chlorine	(Secondary) Residual Chlorine
4	Primary	E	yes	-	-	-	-	-	-	-	-
3	Secondary	C,D	yes	-	-	-	-	-	yes		yes
2	Tertiary	B	yes	yes	yes	-	-	-	yes	yes	yes
1	Tertiary	A	yes	yes	yes	yes	-	-	yes	yes	yes
5a	Tertiary	A to F	yes	yes	yes	yes	-	yes	-	-	yes
5b	Tertiary	B to E	yes	yes	yes	-	yes	-	yes	-	yes

7.6 Costs

A study from 2011 [70] explores the values of the operation and maintenence costs for twentyfour different water treatment plants. The study analyzes the distribution of the costs between energy, staff and other operation and maintenence costs. The results are reproduced in Table 7.9. We see that operation and maintenence costs average around 0.24 $Eurs/m^3$ of which about 20 % is the OnM costs of energy. Another study by the United Nation Environment Programme (UNEP) from 2015 [71] provides a good review of different studies on water purification costs. The report cites the work by Iglesias Esteban [72, 67] in which the operation and investment costs for the different treatment train are discussed. These costs are reproduced in in Table 7.10 with an additional column added to remove the 20% of OnM costs associated with energy consumption. Another study from 2011 [73] gives similar results with OnM costs totaling 0.24 $Eurs/m^3$ with energy and about 0.2 $Eurs/m^3$ without energy. Investment costs were about 0.4 $Eurs/m^3$ for a production of 8.4 hm^3 using an amortization period of 20 years, interest rate of 6% and discount rate of 3.5%. Cabrera (2012) [74] use estimate an average life time of between 20 to 30 years for water treatment plant and use and average OnM cost of 0.423 €/m^3.

Table 7.9: Breakup of operation and maintenence costs of different wastewater treatment plants [70]

Plant Number	Treatment Train	Volume Wastewater processed (m^3)	Cost OnM Energy (€/m^3)	Cost OnM Staff (€/m^3)	Cost OnM Others (€/m^3)	Cost OnM Total (€/m^3)	Cost OnM Total without Energy (€/m^3)	Cost OnM Energy as % of total
WWTP1	1	53935	-	-	-	0	0	
WWTP2	1	51111	0.013	0.024	0.032	0.069	0.056	18.84
WWTP3	1	45227	0.027	0.033	0.018	0.078	0.051	34.62
WWTP4	1	6300	0.039	0.053	0.025	0.117	0.078	33.33
WWTP5	1	14722	0.028	0.015	0.048	0.091	0.063	30.77
WWTP6	1	38634	0.041	0.06	0.077	0.178	0.137	23.03
WWTP7	1	13681	0.084	0.108	0.031	0.223	0.139	37.67
WWTP8	2	20825	0.069	0.074	0.068	0.211	0.142	32.7
WWTP9	2	37735	0.032	0.032	0.1	0.164	0.132	19.51

Table 7.9: Breakup of operation and maintenence costs of different wastewater treatment plants [70]

Plant Number	Treat-ment Train	Volume Wastew-ater pro-cessed (m^3)	Cost OnM Energy (€/m^3)	Cost OnM Staff (€/m^3)	Cost OnM Others (€/m^3)	Cost OnM Total (€/m^3)	Cost OnM Total without Energy (€/m^3)	Cost OnM Energy as % of total
WWTP10	2	42029	0.054	0.082	0.1	0.236	0.182	22.88
WWTP11	2	12707	0.078	0.063	0.068	0.209	0.131	37.32
WWTP12	2	10699	0.072	0.065	0.075	0.212	0.14	33.96
WWTP13	2	7359	0.061	0.153	0.09	0.304	0.243	20.07
WWTP14	3	21290	0.042	0.103	0.06	0.205	0.163	20.49
WWTP15	3	10735	0.055	0.058	0.19	0.303	0.248	18.15
WWTP16	3	7945	0.107	0.061	0.115	0.283	0.176	37.81
WWTP17	4	28870	0.052	0.078	0.107	0.237	0.185	21.94
WWTP18	4	35613	0.045	0.081	0.05	0.176	0.131	25.57
WWTP19	4	14048	0.038	0.105	0.122	0.265	0.227	14.34
WWTP20	4	30584	0.059	0.082	0.135	0.276	0.217	21.38
WWTP21	4	17676	0.101	0.137	0.185	0.423	0.322	23.88
WWTP22	4	23695	0.064	0.094	0.131	0.289	0.225	22.15
WWTP23	5b	12517	0.058	0.133	0.069	0.26	0.202	22.31

Table 7.9: Breakup of operation and maintenence costs of different wastewater treatment plants [70]

Plant Number	Treatment Train	Volume Wastewater processed (m^3)	Cost OnM Energy (€/m^3)	Cost OnM Staff (€/m^3)	Cost OnM Others (€/m^3)	Cost OnM Total (€/m^3)	Cost OnM Total without Energy (€/m^3)	Cost OnM Energy as % of total
WWTP24	5a	8474	0.125	0.103	0.083	0.311	0.186	40.19
Mean		23600.46	0.06	0.08	0.09	0.21	0.16	26.65

Table 7.10: Investment (Invs) and operation and maintenence (OnM) costs of different wastewater treatment process trains [72, 67]

Treatment Train	Treatment Category	Quality	Cost Invs (€/ (m^3/day)	Cost OnM (€/m^3)	Cost OnM (€/m^3) w/o 25% Energy
4	Primary	E	5-11	0.04 - 0.07	0.03 - 0.05
3	Secondary	C,D	9-22	0.04 - 0.07	0.03 - 0.05
2	Tertiary	B	27-47	0.06 - 0.09	0.05 - 0.07
1	Tertiary	A	164-351	0.14 - 0.20	0.11 - 0.15
5b	Tertiary	B,C,D,E	248-405	0.35 - 0.45	0.26 - 0.34
5a	Tertiary	A,B,C,D,E,F	259-458	0.35 - 0.45	0.26 - 0.34

7.7 Energy Consumption

The Spanish Ministry of industry, toursim and commerce published a report in 2010 [75] detailing the energy consumption in water treatment processes grouped by the size of the population being served. The report uses some standard values including an approximate value of $0.2m^3$ of wastewater produced per person. Desalination was reported to produce about 1.5 to 2 hm^3 of water a year and consumed about 1 % of the national energy demand at an average of 3.5 kWh/m^3. At the same time about 3000 hm^3 of municipal water was purified and consumed another 1% of the national energy demand. The average consumption per volume of water without desalination was 0.67 kWh/m^3 [75]. Modern, desalination plants have become more efficient and can produce water using about 2.5 kWh/m^3, however, given the range of technologies and ages of plants it is estimated that desalination technologies consume about 5 kWh/m^3. The energy consumption distribution by process is shown in Table 7.11. As seen in the table the largest consumer of energy in the purification process without desalination are the secondary treatment aeration processes. Other studies [76, 77]also show similar numbers reporting about 55.6% of the energy consumed by the activated sludge aeration process. Based on these studies we estimate different amounts of energy consumption for different treatment processes, summed for the different treatment trains in Spain, as shown in Table 7.12.

Table 7.11: Energy efficiency of different wastewater treatment processes [75]

Process	Power Consumed (kW)	% of Total
Water Line		
Pumping	10,240	3.4
Pretreatment	14,589	4.8
Filtration	13,950	4.6
Primary	64	0
Spetic Tank	0	0
Septic Tank + Biological filter	0	0
Extended Compact Aeration	16,462	5.4
Biodisc Aeration	691	0.2
Mechanical Aeration	40,337	13.2
Aeration Blowers	98,981	32.4
Active sludge aeration	29,284	9.6
Denitrification Aeration	15,063	4.9
Agitation and sludge return	43,446	14.2
Agitation and sludge return + denitrification	805	0.3
Decantation and sludge pumping	4,877	1.6
Tertiary treatment	199	0.1

Table 7.11: Energy efficiency of different wastewater treatment processes [75]

Process	Power Consumed (kW)	% of Total
Sludge Line		
Gravitational thickener	1,493	0.5
Mechanical thickener	3,540	1.2
Direct elimination (wet)	0	0
Dehydration Filter bags	550	0.2
Dehydration Centrifuge	17,103	5.6
Anaerobic digestor and cogeneration	-6,625	-2.2
Total Power (kW)	305,049	100
Population (person)	54,357,571	
Power per person (W/person)	5.61	
Energy in Year (kWh)	2,672,229,240	
Volume treated in Year (hm3)	3,968	
Energy per Volume (kWh/m3)	0.67	

Table 7.12: Estimated energy efficiency of different wastewater treatment processes

Treatment Train	Quality	Total (kWh/m^3)	Primary (0.12 kWh/m^3)	Secondary (0.55 kWh/m^3)	Tertiary (0.00 kWh/m^3)	Desalination (5 kWh/m^3)
4	E	0.12	0.12			
3	C,D	0.67	0.12	0.55		
2	B	0.67	0.12	0.55	0	
1	A	0.67	0.12	0.55	0	
5b	B,C,D,E	5.67	0.12	0.55	0	5
5a	A,B,C,D,E,F	5.67	0.12	0.55	0	5

7.8 Water Efficiency

Section 1.5.3 of the IEAGHG report from 2011 [78] gives the water balance of different wastewater treatment processes as measured in wastewater treatment plants in several different South African powerplants. The report finds that no water is lost in certain processes such as removal of TSS with cartridge filters, removal of residual BOD/COD with activated carbon filters or disinfetion (UV and other chemicals). In general the most water consumptive processes are membrane filtration processes such as ultrafiltration (4%) and reverse osmosis (30%). A summary of the results are provided in Table 7.13. Based on this study we approximate the water efficiency parameters for the different treatment processe trains as shown in Table 7.14.

Table 7.13: Water efficiency of different wastewater treatment processes [78]

Treatment Plant	Power Plant Type	Treatment Processes	Waste Water in (m^3/h)	Water loss (m^3/h)	% Loss
WWTP1	Shell Integrated Gasification Combined Cycle (IGCC) fed with bituminuos coal (without CO2 capture)	Equalization, cooling, chemical conditioning, chemical sludge settling, neutralization, activated sludge process, biological sludge settling, disinfection, chemical and biological sludge treatment	58.7	0.27	0.46
WWTP2	GE IGCC fed with bituminuous coal (without CO2 capture)	Equalization, cooling, chemical conditioning, chemical sludge settling, activated sludge process, biological sludge settling, dual media filtration, heating and chemical conditioning, ammonia stripping, disinfection, chemical and biological sludge treatment	21.91	0.03	0.14
WWTP3	Ultra Super Critical Pulverised Coal (USC PC) fired with lignite (with CO2 Capture)	Eqaulization, chemical conditioning, chemical sludge settlement, sand filters and cartridge filters, ultrafiltration, Reverse Osmosis	73.3	24.4	33.29
WWTP4	Ultra Super Critical Pulverised Coal (USC PC) fired with lignite and oxyfuel technology (with CO2 capture)	Neutralization with caustic soda, Reverse Osmosis	277.4	88.2	31.8

Table 7.13: Water efficiency of different wastewater treatment processes [78]

Treatment Plant	Power Plant Type	Treatment Processes	Waste Water in (m^3/h)	Water loss (m^3/h)	% Loss
WWTP5	Shell IGCC fed with bituminuos coal (with CO2 capture)	Equalization, chemical conditioning, chemical sludge settling, neutralization, activated sludge process, biological sludge settling, disinfection, chemical and biological sludge treatment	163.72	0.42	0.26
WWTP6	Shell IGCC fed with lignite (with CO2 capture)	Equalization, chemical conditioning, chemical sludge settling, dual media filtration, heating and chemical conditioning, ammonia stripping, cooling, neautralization, activated sludge process, chemical and biological sludge treatment, dual media filtration, cartridge filters, ultrafiltration, reverse osmosis	207.5	68.9	33.2
WWTP7	GE IGCC fed with bituminuos coal (with CO2 capture)	Equalization, chemical conditioning, chemical sludge settling, filtration, heating and chemical conditioning, ammonia stripping, cooling, neutralization, activated sludge settling, disinfection, chemical and biological sludge treatment	21.7	0.03	0.14

Table 7.14: Water efficiency of different wastewater treatment processes [78]

Treatment Train	Quality	Water loss (%)
4	E	0
3	CD	0
2	B	0
1	A	4
5b	BCDE	20
5a	ABCDEF	34

7.9 Existing Capacity

The data on water purification in Spain is available for municipal treatment plants (In Spanish: Estaciones de Depuración de Aguas Residuales - EDAR). The quality of water processed in these plants is governed by the Spanish Law (Royal Decree 1620/2007 [68]) which stipulates quality standards as a function of the population aglomeration. The distribution of purification plants in Spain [79] and the aglomeration size served by the plant is shown in Figure 7.4.

The distribution of water purified, aggregated by basin for different purification plants with different treatment processes are shown in Table 7.15 [79]. The treatment options as given in the database were grouped together into Primary, Secondary and Tertiary treatment processes which were assumed to be able to treat waters to different levels of quality from Table 7.8. This modified table is shown in Table 7.16.

Similarily the installed capacity of purification systems by basin is given in the same database [79]. The original data is shown in Table 7.17 and the corresponding modified table is shown in Table 7.18.

In order to reuse treated wastewater, corresponding pipes need to be layed and the reclaimed water quality has to be ensured for the particular use it being considered for. Water reuse in Spain has been documented in a few different government sources since the passing of the Royal Decree 1620/2007 [68]. Future water reutilization expansion plans are also presented in the Spanish National Reutilization Plan [69]. The values in the plan have been reproduced below in Table 7.19. FUrther details on the subsector distirbution of reclaimed water use is stored in the "Digital White Book of Water" [80]. This data has been compared with the regulations from Table 7.7 and is given in Table 7.20 and Table 7.21.

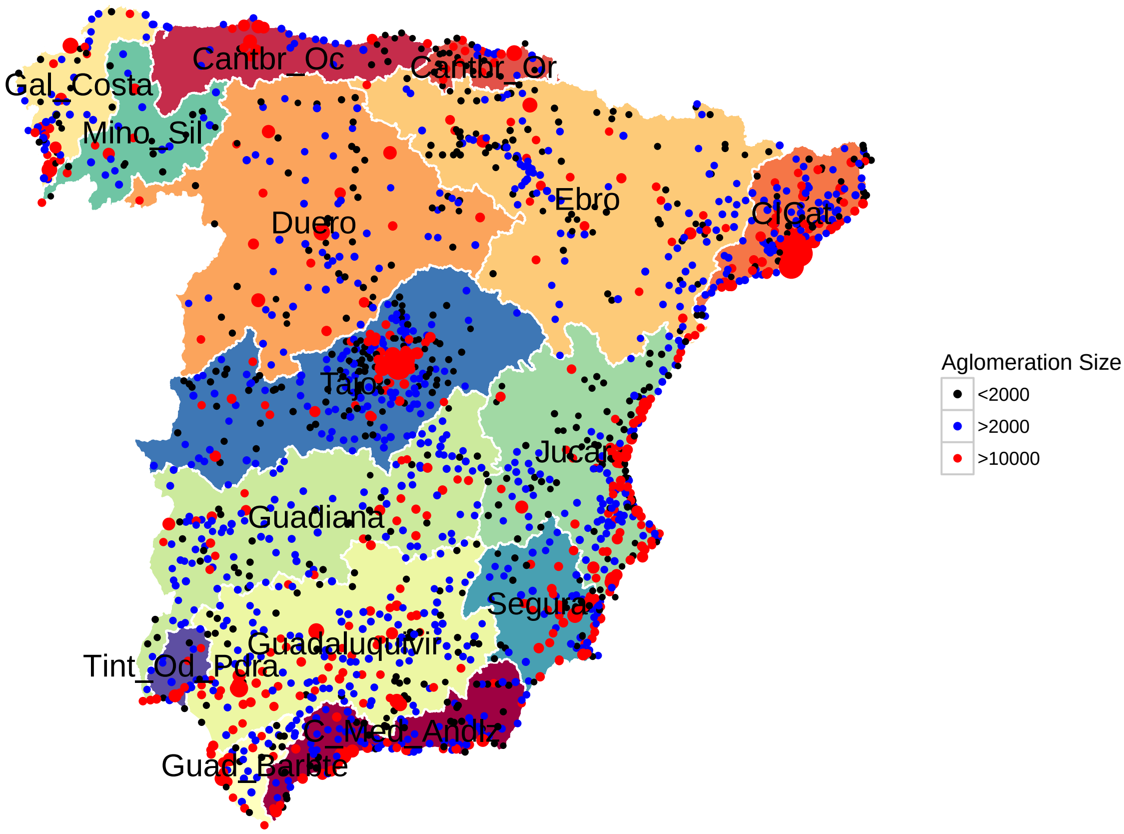

Figure 7.4: Distribution of municipal treatment plants in Spain by aglomeration served

Table 7.15: Water volume treated in different basins at different plants with different treatment processes (hm^3/yr) [79]

Basin	Pretreatment	Primary	N	N + P	Secondary	Secondary + Tertiary	N + Tertiary	N + P + Tertiary	Unspecified	Sum
GalCosta	2.45	0.00	12.48	1.75	57.52	0.00	4.08	1.54	9.22	89.04
MinoSil	0.00	0.00	8.24	0.59	11.35	0.00	0.00	0.00	6.52	26.70
CantbrOc	8.15	3.50	25.48	0.00	36.83	0.00	0.00	0.00	7.14	81.10
CantbrOr	0.00	0.00	151.02	0.00	1.07	0.00	0.00	0.00	4.88	156.97
Duero	0.00	0.70	99.11	0.00	47.70	0.00	0.00	0.00	9.30	156.81
Tajo	0.00	0.00	86.37	11.14	575.84	0.00	4.92	0.00	22.27	700.54
Guadiana	0.00	2.21	19.02	9.51	42.19	0.00	0.72	0.64	19.88	94.17
TintOdP-dra	0.00	5.14	1.99	0.00	13.02	0.00	0.00	0.00	1.07	21.22
Guadlqvir	0.00	2.35	2.93	0.00	224.22	0.00	1.09	0.00	23.83	254.42
Guad-Barbte	0.00	2.51	1.28	0.00	54.88	0.00	5.37	0.00	2.76	66.80
CMedAn-dlz	0.00	0.31	20.51	0.00	144.05	46.00	0.00	0.00	7.05	217.92
Segura	0.00	0.00	65.54	0.00	49.36	4.23	6.15	0.83	16.71	142.82
Jucar	3.88	24.88	40.05	0.00	253.45	66.03	59.55	0.00	38.88	486.72
Ebro	0.00	0.43	73.11	0.00	104.82	0.44	0.00	0.00	25.10	203.90
CICat	0.00	1.10	48.77	0.00	390.53	0.00	0.00	0.00	42.13	482.53
Total	14.48	43.13	655.90	22.99	2006.83	116.70	81.88	3.01	236.74	3181.66

Table 7.16: Water volume treated in different basins at different plants grouped by treatment processes categories and water quality (hm^3/yr)

Basin	Primary (3CD,4E)[1]	Secondary (2B,3CD,4E)	Tertiary (all AtoE)	Sum
GalCosta	2.45	76.36	10.23	89.04
MinoSil	0.00	23.44	3.26	26.70
CantbrOc	11.65	65.88	3.57	81.10
CantbrOr	0.00	154.53	2.44	156.97
Duero	0.70	151.46	4.65	156.81
Tajo	0.00	684.49	16.05	700.54
Guadiana	2.21	80.66	11.30	94.17
TintOdPdra	5.14	15.54	0.54	21.22
Guadlqvir	2.35	239.06	13.01	254.42
GuadBarbte	2.51	57.54	6.75	66.80
CMedAndlz	0.31	168.09	49.52	217.92
Segura	0.00	123.25	19.57	142.82
Jucar	28.76	312.94	145.02	486.72
Ebro	0.43	190.48	12.99	203.90
CICat	1.10	460.37	21.07	482.53
Total	57.61	2804.09	319.96	3181.66

Notes:

1:The numbers (2,3,4) refers to the treatment trains from Table 7.8 and the letters (A,B,C,D,E,F) refer to the qualities from the same table.

Table 7.17: Water purification capacity in different basins at different plants with different treatment processes (hm^3/yr) [79]

Basin	Pretreatment	Primary	N	N + P	Secondary	Secondary + Tertiary	N + Tertiary	N + P + Tertiary	Unspecified	Sum
GalCosta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	27.91	27.91
MinoSil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	55.24	55.24
CantbrOc	29.16	8.64	78.19	0.00	0.56	0.00	0.00	0.00	438.45	555.00
CantbrOr	0.00	0.00	176.94	0.00	3.60	0.00	0.00	0.00	1267.44	1447.98
Duero	0.00	0.00	100.97	0.00	63.27	0.00	0.00	0.00	21.99	186.23
Tajo	0.00	0.00	118.83	11.32	699.55	0.00	15.16	0.00	222.36	1067.22
Guadiana	0.00	5.80	22.21	0.00	52.81	0.00	0.00	0.00	2.90	83.72
TintOdPdra	0.00	25.66	0.00	0.00	26.96	0.00	0.00	0.00	0.00	52.62
Guadlqvir	0.00	5.47	14.06	0.00	341.88	0.00	1.80	0.00	64.25	427.46
GuadBarbte	0.00	0.00	1.85	0.00	91.46	0.00	10.47	0.00	1.69	105.47
CMedAndlz	0.00	0.00	25.92	0.00	184.34	98.01	0.00	0.00	3.69	311.96
Segura	0.00	0.00	73.52	0.00	107.59	16.51	11.13	1.00	115.56	325.31
Jucar	5.69	7.50	67.35	0.00	294.47	79.78	91.03	0.00	805.42	1351.24
Ebro	0.00	0.00	81.05	0.00	250.18	0.00	0.00	0.00	515.37	846.60
CICat	0.00	2.08	113.76	0.00	763.10	0.00	0.00	0.00	187.21	1066.15
Total	34.85	55.15	874.65	11.32	2879.77	194.30	129.59	1.00	3729.48	7910.11

Table 7.18: Water purification capacity in different basins at different plants grouped by treatment processes categories and water quality (hm^3/yr)

Basin	Primary (3CD,4E)[1]	Secondary (2B,3CD,4E)	Tertiary (all AtoE)	Sum
GalCosta	0.00	13.96	13.96	27.91
MinoSil	0.00	27.62	27.62	55.24
CantbrOc	37.80	297.98	219.22	555.00
CantbrOr	0.00	814.26	633.72	1447.98
Duero	0.00	175.24	10.99	186.23
Tajo	0.00	940.88	126.34	1067.22
Guadiana	5.80	76.47	1.45	83.72
TintOdPdra	25.66	26.96	0.00	52.62
Guadlqvir	5.47	388.06	33.92	427.46
GuadBarbte	0.00	94.16	11.31	105.47
CMedAndlz	0.00	212.10	99.86	311.96
Segura	0.00	238.89	86.42	325.31
Jucar	13.19	764.53	573.52	1351.24
Ebro	0.00	588.91	257.69	846.60
CICat	2.08	970.47	93.61	1066.15
Total	90.00	5630.48	2189.63	7910.11

Notes:

1:The numbers (2,3,4) refers to the treatment trains from Table 7.8 and the letters (A,B,C,D,E,F) refer to the qualities from the same table.

Table 7.19: Reclaimed water use in different basins (hm^3/yr)

Basin	Capacity Reutilizacion (m^3/day) 2008	Capacity (hm^3/yr) 2008	Reused 2008 (hm^3/yr)	Reused 2015 (hm^3/yr)	Plan Reuse post 2015 (hm^3/yr)
MinoSil	-	-	-	6	6
CantbrOc	-	-	-	10	31
CantbrOr	9,529	3.5	-	10	31
Duero	-	-	-	3	63
Tajo	331,013	120.8	15	53	284
Guadiana	3,870	1.4	-	21	45
TintOdPdra	-	-	-	-	-
Guadlqvir	-	-	3	10	10
GuadBarbte	41,235	15.1	-	-	-
CMedAndlz	323,898	118.2	-	-	-
Segura	192,000	70.1	69	159	172
Jucar	923,175	337	115	168	187
Ebro	75,776	27.7	12	23	31
CICat	515,624	188.2	-	-	-
GalCosta	-	-	-	-	-
Total	2,416,120	881.9	214	463	860

Table 7.20: Reclaimed water use in different basins by use (hm^3/yr) [80]

Sector		Urban Residential	Urban Residential	Urban - Services	Environmental - Irrigation Non Public	Environmental - Irrigation Non Public	Urban - Services	Urban - Services	Agriculture	Agriculture - Edible	Agriculture - Edible
Original Category in Spanish		USO DOMICILIARIO	USO URBANO	RIEGO PARQUES Y JARDINES	RIEGO PARQUE FORESTAL	RIEGO ZONAS VERDES	RIEGO ZONAS DEPORTIVAS	RIEGO BALDEO DE CALLES	RIEGOS AGRICOLAS	RIEGO AGRICOLA DE CONSUMO CRUDO	RIEGO AGRICOLA DE CONSUMONO CRUDO
Subsector		1.1a, 1.1b	1.2a to 1.2d	1.2a	5.3a	5.3a	1.2a	1.2b	2.2a to 2.3c	2.1a	2.2a
Quality Required	Total	A	B	B	E	E	B	B	B,C,D	B	C
MinoSil	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	-	-	-	-	-	-	-	-	-	-	-
CantbrOr	0	-	0	-	-	-	-	-	-	-	-
Duero	-	-	-	-	-	-	-	-	-	-	-
Tajo	9.07	-	1.72	0	-	4.3	-	-	-	-	-
Guadiana	7.05	-	-	-	-	-	-	-	0.38	-	1.27
TintOdPdra	-	-	-	-	-	-	-	-	-	-	-

Table 7.20: Reclaimed water use in different basins by use (hm^3/yr) [80]

Sector		Urban Residential	Urban Residential	Urban - Services	Environmental - Irrigation Non Public	Environmental - Irrigation Non Public	Urban - Services	Urban - Services	Agriculture	Agriculture - Edible	Agriculture - Edible
Guadlqvir	12.61	-	0	-	-	-	-	-	-	-	9.9
Guad-Barbte	15.1	-	3.24	-	-	-	-	-	0.92	8.16	0.12
CMedAndlz	36.36	-	7.45	-	-	-	-	-	-	-	0.02
Segura	65.25	-	0.23	0.1	-	-	-	-	-	-	-
Jucar	111.82	-	2	1.5	-	-	-	-	-	-	-
Ebro	12.57	-	0.95	-	-	-	-	-	-	5.37	-
CICat	163.81	-	5.07	-	-	-	-	-	11.65	4.66	0.07
GalCosta	-	-	-	-	-	-	-	-	-	-	-
Total	433.65	-	20.66	1.61	-	4.3	-	-	12.94	18.19	11.38

Table 7.21: Reclaimed water use in different basins by use (hm^3/yr) [80]

Sector	Agriculture - Edible	Agriculture - Crops	Agriculture - Crops	Agriculture - Crops	Recreational - Golf	Industry - Process	Recreational - Ornamental Non Public	Agriculture - Edible	Environmental - Aquifers	
Original Category in Spanish	RIEGO AGRICOLA DE PASTOS	RIEGO AGRICOLA INDUSTRIAL	RIEGO AGRICOLA FORESTAL	RIEGO AGRICOLA INVERNADERO	CAMPOS DE GOLF	USO INDUSTRIAL	ESTANQUES	ACUICULTURA	ACUIFEROS	OTROS USOS
Subsector	2.2b	2.3c	2.3a	2.3b	4.1a	3.1a, 3.1b, 3.1c	4.2a	2.2c	5.1a, 5.2a	
Quality Required	C	D	D	D	B	D, D, C	D	C	C,A	
MinoSil	-	-	-	-	-	-	-	-	-	-
CantbrOc	-	-	-	-	-	-	-	-	-	-
CantbrOr	-	-	-	-	-	-	-	-	-	-
Duero	-	-	-	-	-	-	-	-	-	-
Tajo	-	-	-	-	3.05	-	-	-	-	-
Guadiana	-	-	-	-	2.67	-	-	-	2.74	-
TintOdPdra	-	-	-	-	-	-	-	-	-	-
Guadlqvir	0	1.52	-	-	0.41	0.78	-	-	-	-

Table 7.21: Reclaimed water use in different basins by use (hm^3/yr) [80]

Sector	Agriculture - Edible	Agriculture - Crops	Agriculture - Crops	Agriculture - Crops	Recreational - Golf	Industry - Process	Recreational - Ornamental Non Public	Agriculture - Edible	Environmental - Aquifers	
Guad-Barbte	0.01	-	0.05	-	2.43	0.18	-	-	-	-
CMedAndlz	-	-	-	-	28.89	-	-	-	-	-
Segura	-	64.68	-	-	0.25	-	-	-	-	-
Jucar	-	104.44	-	-	3.83	-	-	-	-	0.05
Ebro	-	-	-	-	-	-	-	-	-	6.25
CICat	0.06	2.61	-	-	7.28	1.44	-	2.25	16.77	111.95
GalCosta	-	-	-	-	-	-	-	-	-	-
Total	0.07	173.24	0.05	-	48.8	2.4	-	2.25	19.51	118.24

7.10 Future Predictions and Climate Change

Given the small percentage of purified water that is currently reused in Spain, there is a lot of potential for further expansion. As mentioned before municipal wastewater provides a steady realiable source of water close to urban centers. With increasing pressures on water resources in some regions, reclaimed water reuse may be a suitable alterantive to free freshwater for potable uses. The main barrier in reusing already purified wastewater is the construction of separate reclaimed water pipelines. The costs and other details of pipilines and distribution is discussed in the corresponding section. Even in regions where climate change is expected to decrease natural resources, municipal wastewater will remain steady since, water for human consumption and urban uses is given priority over other uses and water will thus be diverted for human consumption from other sectors.

Chapter 8

Water Transfers

8.1 Key Points

- Long distance water transfers can consume high amounts of energy depending on the net elevation change of the route taken
- Energy costs can be the highest part of the annual costs related to long distance transfers

8.2 Introduction

Interbasin transfers are an option available to move water from a water rich basin to one suffering for water scarcity or shortage. In Spain, one of the main water issues is the water shortage and drought in the south eastern basins. A national plan was devised to transfer water from the Ebro river basin to these south eastern basins in 2000. The economic and environmental feasibility of the plan was heavily debated and finally it was abandoned by a change in the government. The debate over the transfer raised important issues such as the environmental impacts in the original basin and the benefits of other options such as desalination, water reuse and local water efficiency. In this section we look at the investment and operation costs for different interbasin possibilities in Spain as well as the corresponding energy consumption and water losses. The parameters will be used to compare with the other alternatives available to solve regional water availability issues.

8.3 Parameter Summary

The different parameters for interbasin water transfers are summarized in Table 8.1. The cost parameters are given as per unit length and are thus related to the distances between the different basins as shown in Table 8.10. The energy parameter was calculated per unit length considering the elevation gains, internal friction and pumping efficiency (65%).

Table 8.1: Interbasin transfer parameters used in model

Parameter	Name in Model	Value
Energy Consumption (kWh/m3)	p_nrg_trnsf(b,b)	See Table 8.18
Water loss (%)	s_wloss_trnsf	25
Cost Investment (2012 €/ (m^3/month) / m)	p_cost_trnsf_Inv	1.09E-04
Cost OnM (2012 €/ m^3 / m)	p_cost_trnsf_Inv	1.13E-07
Life time (years)	s_life_trnsf	50
Interest Rate (%)	s_intrate_trnsf	6

Notes:
1:O&M costs exclude energy costs.

8.4 Worked Example

An example is used to demonstrate the use of the parameters summarized in Table 8.1. The example is based on the extensively studied Ebro river basin transfer in order to compare the results with final results from other studies. The transfer consists of moving 315 hm^3 of water to the Jucar basin, 450 hm^3 to the Segura basin and 95 hm^3 to the Andalusian basins as shown in Figure 8.1 [81].

We assume there is no existing capacity and use an interest rate of 6% with a project lifetime of 50 years as reported in the National Hydrological Plan (NHP) (2000) [82] . The results of the example are shown in Tables 8.2, 8.3, 8.4 and 8.5. The investment cost is estimated to be about 4.5 billion 2012 €(3.2 billion 2000 €) which is comparable to the estimate by the NHP of about 4 billion 2000 € [83, 81].

The NHP uses a value of 0.03 €/ kWh for the price of electricity. We convert this to 0.042 €/ kWh (using a factor of 1.41) to account for inflation between 2000 and 2012 to be consistent with other calculations in this study. This study shows average costs per cubic meter of water of 0.97 2012 €/ m^3 (0.69 2000 €/ m^3). The price increases along the transfer from 0.5 to 1.5

2012 €/ m^3 (0.36 to 1.06 2000 €/ m^3). The NHP calculated an average cost of 0.3 €/ m^3 while a study by the WWF [84] calculated an average cost of 0.73 €/ m^3 when accounting for factors such as amortisation, climate change, losses and treatment.

The path chosen for the transfer will impact the results significantly, but the example shows that the methodology used gives a reasonable estimate of the costs and energy consumption (the energy consumption being slightly higher than that in other studies).

Figure 8.1: Planned water transfers in the Ebro river basin transfer plan (from Hernandez 2014) [81]

Table 8.2: Example for investment costs for Ebro inter-basin water transfer

Section	Length	Vol (hm3)	Total Investment (Billion 2012 €)	Annual Amortization (Billion 2012 €)	Annual Amortization (2012 €/m3)	Cummulative Costs (2012 €/ m3)
Ebro - Jucar	386.9	860	3.03	0.19	0.22	0.22
Jucar - Segura	233.3	545	1.16	0.07	0.13	0.36
Segura - Andalucia	387.3	95	0.34	0.02	0.22	0.58
Total			4.53	0.29		

Table 8.3: Example for O&M costs for Ebro inter-basin water transfer

Section	Length	Vol (hm3)	Total Annual OnM (Billion 2012 €)	OnM Cost per Vol (2012 €/m3)	Cummulative Costs (2012 €/m3)
Ebro - Jucar	386.9	860	0.04	0.04	0.04
Jucar - Segura	233.3	545	0.01	0.03	0.07
Segura - Andalucia	387.3	95	0.00	0.04	0.11
Total			0.06		

Table 8.4: Example for energy costs for Ebro inter-basin water transfer

Section	Length	Vol (hm3)	Energy (kWh/m3)	Total Energy (kWh)	Cost of Electricty (2012 €/kWh)	Total Energy Cost per Year (Billion 2012 €)	Energy Cost per vol (2012 €/m3)	Cummulative Costs (2012 €/m3)
Ebro - Jucar	386.9	860	5.55	4.77E+9	0.04	0.20	0.23	0.23
Jucar - Segura	233.3	545	5.31	2.89E+9	0.04	0.12	0.22	0.46
Segura - Andalucia	387.3	95	8.52	8.09E+8	0.04	0.03	0.36	0.82
Total						0.36		

Table 8.5: Example for total costs for Ebro inter-basin water transfer

Section	Investment Costs Per Section (2012 €/m3)	OnM Costs Per Section (2012 €/m3)	Energy Costs Per Section (2012 €/m3)	Total Costs Per Section (2012 €/m3)	Cummulative Costs (2012 €/m3)	Cummulative Costs (2000 €/m3)
Ebro - Jucar	0.22	0.04	0.23	0.50	0.50	0.36
Jucar - Segura	0.13	0.03	0.22	0.39	0.89	0.63
Segura - Andalucia	0.22	0.04	0.36	0.63	1.52	1.08
Average	0.19	0.04	0.27	0.51	0.97	0.69

8.5 Costs

For long distance water transfers, costs are studied based on the economic analysis of water transfer systems in Spain as reported in detail in the National Hydrological Plan (NHP) written in 2000 [82] and updated in 2005. Costs associated with long distance transfers are closely related to the path chosen for the pipelines, the number of tunnels, bypass wiers, culverts, trenches, aqueducts, siphons and other infrastructure needed. The primary operation costs will depend on the energy used in lifting the water through the cummulative water head long the transfer, less the energy generated using hydroelectric units. The NHP differentiates between, investment costs, operation costs associated with energy and other operation costs associated with administration and maintenence. Non-energy operation and maintenence costs are proposed at 1% of the total investment costs and administration costs are estimated at 0.2% of the total investment costs [82].

The NHP considers several different transfer sections as shown in Figure 8.2. For each segment, different combinations of infrastructure elements (siphons, aqueducts, canals etc.) are considered. The investment costs of each element is considered based on engineering estimates as shown in the example extracts from the NHP in Figure 8.3 and Figure 8.4 for an example dam and canal respectively. For each section the total investment costs for different water flow quantities are calculated considering the required infrastructure elements as shown in the example extract in Figure 8.5. A summary of the costs for several different sections are summarized in 8.6. The costs are converted from the Spanish currency at the time, the Spanish Peseta, to Euros using the conversion of 1 Peseta to 0.006 Euros. Next an inflation factor of 1.41 is used to account for inflation from the year 2000 to 2012. The final investment costs are given as 2012 Eurs per cubic meter per meter length. These can then be multiplied by the distances between different basins from the matrix presented in Table 8.10 as well as the required volume of water transfer per month to get the investment costs required. Operation costs in 2012 Eurs per cubic meter of water transfered can similarily be computed by multiplying the operation costs per cubic meter per length, by the distances corresponding distances.

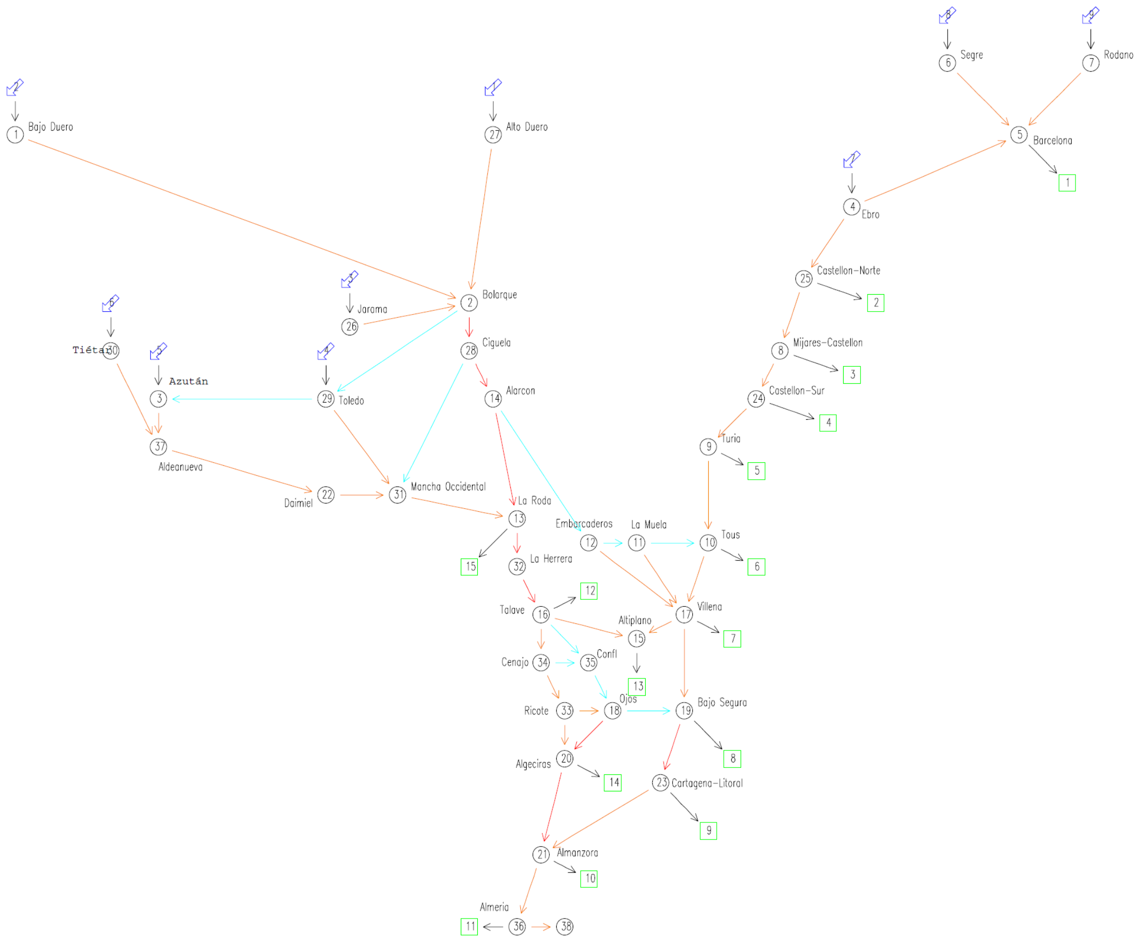

Figure 8.2: Water transfer routes considered in the Spanish National Hydrological Plan [82]

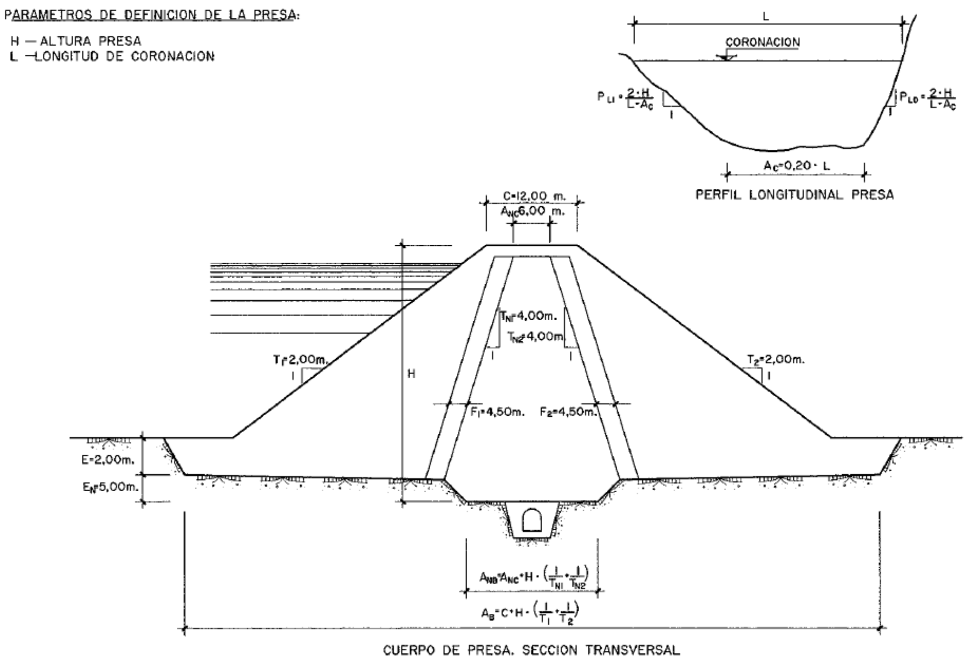

Figura 2. Presas de materiales sueltos. Diseño tipo

- Talud de la presa aguas arriba: 1:2,00 (V:H)
- Talud de la presa aguas abajo: 1:2,00 (V:H)
- Anchura de coronación: 12,00 m.
- Anchura de filtros: 9,00 m.
- Anchura de coronación del núcleo: 6,00 m.
- Talud del núcleo aguas arriba: 1:4,00 (H:V)
- Talud del núcleo aguas abajo: 1:4,00 (H:V)
- Excavación de cimientos de presa: 2,00 m.
- Empotramiento del núcleo: 5,00 m.
- Anchura del cauce: 20% de la long. de coronación
- Laderas de la cerrada: Simétricas

La valoración del cuerpo de la presa se realiza midiendo las unidades de obra siguientes, aplicándolas los correspondientes precios unitarios:

- Excavación en cimientos: 260 Pts./m^3
- Escollera en cuerpo de presa: 850 Pts./m^3
- Material arcilloso en núcleo: 720 Pts./m^3
- Material filtrante: 1.280 Pts./m^3

Figure 8.3: Extract of an example of an engineering estimate of a dam structure from the Spanish National Hydrological Plan [82]

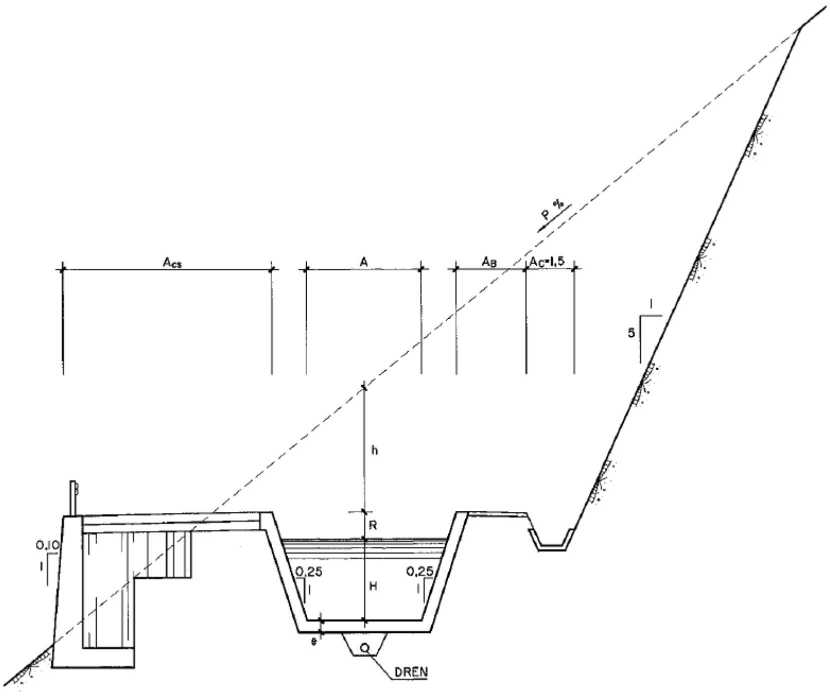

Figura 7. Canales en roca. Sección tipo

En cualquier caso, los parámetros de diseño que caracterizan las secciones tipo anteriores, además del caudal de diseño, son los que se indican en las tablas adjuntas:

	$0 < q < 10$ m^3/s	10 m^3/s $< q < 20$ m^3/s	20 m^3/s $< q < 30$ m^3/s
Pendiente del canal	0,0001	0,0001	0,0001
Anchura base canal (m)	2,5	2,5 a 3,5	3,5
Talud cajeros (H/V)	1,5	1,5	1,5
Espesor revestimiento (m)	0,15	0,15	0,15
Ancho camino servicio (m)	4,0 a 6,0	6,0	6,0
Ancho banqueta (m)	2,0	2,0 a 3,0	3,0
Ancho cuneta (m)	2,5	2,5	2,5
Resguardo (m)	0,2 a 0,3	0,3 a 0,5	0,5 a 0,65
Prof.enterramiento (m)	0,5 a 1,0	1,0 a 2,0	2,0 a 3,0
Pendiente ladera (%)	30	30	30
Talud desmonte (V/H)	1,00	1,00	1,00
Talud terraplén (H/V)	1,50	1,50	1,50

Tabla 2. Canales en tierras. Parámetros de diseño

Figure 8.4: Extract of an example of an engineering estimate of a canal structure from the Spanish National Hydrological Plan [82]

						q (m^3/s)											
						5,0		10,0		25,0		35,0		45,0		50,0	
	A (m)	L (m)	V (m3)	H (m)	Medición	Importe unitario (Mpts/ud)	Importe parcial (M Pts)	Importe unitario (Mpts/ud)	Importe parcial (M Pts)	Importe unitario (Mpts/ud)	Importe parcial (M Pts)	Importe unitario (Mpts/ud)	Importe parcial (M Pts)	Importe unitario (Mpts/ud)	Importe parcial (M Pts)	Importe unitario (Mpts/ud)	Importe parcial (M Pts)
1.- ELEVACION CUEVAS DE VINROMA							1.856		3.282		7.190		9.530		11.677		12.682
Ud Estación de bombeo (1,33 q)				103,0	1	1.162	1.162	2.112	2.112	4.716	4.716	6.272	6.272	7.692	7.692	8.351	8.351
m Tubería de impulsión (1,33 q)					1.583	0,169	268	0,293	464	0,677	1.072	0,945	1.496	1,222	1.934	1,363	2.157
Ud Balsa de modulación			21600.q		2	213	426	353	706	701	1.402	881	1.762	1.026	2.051	1.087	2.174
2.- CANAL					31.745		3.638		4.359		6.977		8.727		10.139		10.629
m Sección en roca (q)					19.999	0,132	2.640	0,161	3.220	0,269	5.380	0,343	6.860	0,403	8.060	0,424	8.480
m Sección en tierra (q)					11.746	0,085	998	0,097	1.139	0,136	1.597	0,159	1.868	0,177	2.079	0,183	2.149
3.- TUNELES							4.681		6.328		10.064		11.864		13.434		14.197
m Túnel (q); P.K. 15+716					15249	0,307	4.681	0,415	6.328	0,660	10.064	0,778	11.864	0,881	13.434	0,931	14.197
4.- SIFONES					14.886		2.382		4.585		10.554		14.008		17.060		18.429
m Sifón (q); P.K. 1+668					446	0,160	71	0,308	137	0,709	316	0,941	420	1,146	511	1,238	553
m Sifón (q); P.K. 11+706					297	0,160	48	0,308	92	0,709	211	0,941	280	1,146	340	1,238	368
m Sifón (q); P.K. 13+230					156	0,160	25	0,308	48	0,709	111	0,941	147	1,146	179	1,238	193
m Sifón (q); P.K. 13+457					766	0,160	123	0,308	236	0,709	543	0,941	721	1,146	878	1,238	949
m Sifón (q); P.K. 14+310					1.357	0,160	217	0,308	418	0,709	962	0,941	1.277	1,146	1.555	1,238	1.680
m Sifón (q); P.K. 31+038					383	0,160	61	0,308	118	0,709	272	0,941	361	1,146	439	1,238	475
m Sifón (q); P.K. 33+982					888	0,160	142	0,308	274	0,709	630	0,941	836	1,146	1.018	1,238	1.100
m Sifón (q); P.K. 35+623					521	0,160	83	0,308	161	0,709	370	0,941	491	1,146	597	1,238	645
m Sifón (q); P.K. 37+774					1.275	0,160	204	0,308	393	0,709	904	0,941	1.200	1,146	1.461	1,238	1.579
m Sifón (q); P.K. 39+141					516	0,160	83	0,308	159	0,709	366	0,941	486	1,146	592	1,238	639
m Sifón (q); P.K. 39+726					813	0,160	130	0,308	251	0,709	577	0,941	765	1,146	932	1,238	1.007
m Sifón (q); P.K. 40+633					489	0,160	78	0,308	151	0,709	347	0,941	460	1,146	560	1,238	605
m Sifón (q); P.K. 41+457					295	0,160	47	0,308	91	0,709	209	0,941	278	1,146	338	1,238	365
m Sifón (q); P.K. 42+203					404	0,160	65	0,308	124	0,709	286	0,941	380	1,146	463	1,238	500
m Sifón (q); P.K. 43+700					229	0,160	37	0,308	70	0,709	162	0,941	215	1,146	262	1,238	283
m Sifón (q); P.K. 45+894					386	0,160	62	0,308	119	0,709	274	0,941	363	1,146	443	1,238	478
m Sifón (q); P.K. 47+614					405	0,160	65	0,308	125	0,709	287	0,941	381	1,146	464	1,238	501
m Sifón (q); P.K. 49+020					352	0,160	56	0,308	108	0,709	249	0,941	331	1,146	403	1,238	436
m Sifón (q); P.K. 50+397					329	0,160	53	0,308	101	0,709	233	0,941	310	1,146	377	1,238	407
m Sifón (q); P.K. 50+894					2.685	0,160	430	0,308	827	0,709	1.904	0,941	2.527	1,146	3.077	1,238	3.324
m Sifón (q); P.K. 57+192					814	0,160	130	0,308	251	0,709	577	0,941	766	1,146	933	1,238	1.007
m Sifón (q); P.K. 59+292					649	0,160	104	0,308	200	0,709	460	0,941	611	1,146	744	1,238	804
m Sifón (q); P.K. 63+033					429	0,160	69	0,308	132	0,709	304	0,941	404	1,146	492	1,238	532
PRESUPUESTO DE EJECUCION MATERIAL (M Pts.)							12.558		18.555		34.786		44.129		52.310		55.937
GASTOS GENERALES Y BENEFICIO INDUSTRIAL (23%) (M Pts.):							2.888		4.268		8.001		10.150		12.031		12.866
TOTAL (m Pts.)							15.446		22.823		42.786		54.278		64.341		68.803
I.V.A. (16%) (M Pts.):							2.471		3.652		6.846		8.685		10.295		11.008
PRESUPUESTO DE EJECUCION POR CONTRATA (M Pts.):							17.917		26.474		49.632		62.963		74.636		79.811
PRESUPUESTO CONOCIMIENTO DE LA ADMINISTRACIÓN (M Pts.):							19.001		28.076		52.635		66.772		79.151		84.640

Figure 8.5: Example investment cost calculations from the Spanish National Hydrological Plan [82]

Table 8.6: Summary of investment costs for seleted transfer sections from the Spanish National Hydrological Plan [82]

Transfer Section	Flow (m^3/s)	Flow (hm^3 / month)	Length (km)	Total Investment (2000 MESP)	Total Investment (MEUR 2012)	Volume per year (hm^3)	Total Investment per flow per length 2012 EUR / (m^3/s) / m	Total Investment per flow per month per length 2012 EUR / (m^3/month) / m	Annual OnM w/o Energy (1.2% of total Invest-ment)(2012 MEUR / year	Annual OnM w/o Energy (2012EUR /(m^3) / m)	Coefficient of Energy (kWh / m^3)
Ebro-Barcelona	7	18.14	179.15	48571	410.91	217.73	327.66	1.26E-04	4.93	1.26E-07	0.9
Ebro-Barcelona	10	25.92	179.15	68326	578.04	311.04	322.65	1.24E-04	6.94	1.24E-07	0.8
Ebro-Barcelona	15	38.88	179.15	88201	746.18	466.56	277.67	1.07E-04	8.95	1.07E-07	0.8
Ebro-Barcelona	20	51.84	179.15	107732	911.41	622.08	254.37	9.81E-05	10.94	9.81E-08	0.8
Ebro-Barcelona	25	64.80	179.15	126911	1073.67	777.60	239.72	9.25E-05	12.88	9.25E-08	0.8
Ebro-Barcelona	35	90.72	179.15	162615	1375.72	1088.64	219.40	8.46E-05	16.51	8.46E-08	0.8
Ebro-Castellon Norte	5	12.96	108.88	23579	199.48	155.52	366.44	1.41E-04	2.39	1.41E-07	0.7
Ebro-Castellon Norte	10	25.92	108.88	32012	270.82	311.04	248.74	9.60E-05	3.25	9.60E-08	0.7
Ebro-Castellon Norte	25	64.80	108.88	58629	496	777.60	182.23	7.03E-05	5.95	7.03E-08	0.6
Ebro-Castellon Norte	35	90.72	108.88	75053	634.95	1088.64	166.63	6.43E-05	7.62	6.43E-08	0.6
Ebro-Castellon Norte	45	116.64	108.88	88920	752.26	1399.68	153.54	5.92E-05	9.03	5.92E-08	0.6
Ebro-Castellon Norte	50	129.60	108.88	94494	799.42	1555.20	146.85	5.67E-05	9.59	5.67E-08	0.6
Turia-Villena	5	12.96	80.00	27003	228.45	155.52	571.15	2.20E-04	2.74	2.20E-07	1.4
Turia-Villena	10	25.92	80.00	40842	345.52	311.04	431.92	1.67E-04	4.15	1.67E-07	1.4
Turia-Villena	25	64.80	80.00	77450	655.23	777.60	327.63	1.26E-04	7.86	1.26E-07	1.4
Turia-Villena	35	90.72	80.00	97599	825.69	1088.64	294.90	1.14E-04	9.91	1.14E-07	1.3
Turia-Villena	45	116.64	80.00	114238	966.45	1399.68	268.47	1.04E-04	11.60	1.04E-07	1.3
Turia-Villena	50	129.60	80.00	121159	1025.01	1555.20	256.27	9.89E-05	12.30	9.89E-08	1.3
Cartagena litoral - Almanzora	5	12.96	106.49	28857	244.13	155.52	458.49	1.77E-04	2.93	1.77E-07	0.7
Cartagena litoral - Almanzora	10	25.92	106.49	43201	365.48	311.04	343.20	1.32E-04	4.39	1.32E-07	0.7
Cartagena litoral - Almanzora	15	38.88	106.49	57428	485.84	466.56	304.15	1.17E-04	5.83	1.17E-07	0.7
Cartagena litoral - Almanzora	20	51.84	106.49	71298	603.18	622.08	283.20	1.09E-04	7.24	1.09E-07	0.6
Cartagena litoral - Almanzora	30	77.76	106.49	98057	829.56	933.12	259.66	1.00E-04	9.95	1.00E-07	0.6
Cartagena litoral - Almanzora	35	90.72	106.49	110780	937.2	1088.64	251.45	9.70E-05	11.25	9.70E-08	0.6
Alto Duero - Bolarque	6	15.55	135.00	44628	377.55	186.62	466.11	1.80E-04	4.53	1.80E-07	0.9
Alto Duero - Bolarque	12	31.10	135.00	63659	538.56	373.25	332.44	1.28E-04	6.46	1.28E-07	0.8
Alto Duero - Bolarque	18	46.66	135.00	82030	693.97	559.87	285.58	1.10E-04	8.33	1.10E-07	0.9

Table 8.6: Summary of investment costs for seleted transfer sections from the Spanish National Hydrological Plan [82]

Transfer Section	Flow (m^3/s)	Flow (hm^3 / month)	Length (km)	Total Investment (2000 MESP)	Total Investment (MEUR 2012)	Volume per year (hm^3)	Total Investment per flow per length 2012 EUR / (m^3/s) / m	Total Investment per flow per month per length 2012 EUR / (m^3/month) / m	Annual OnM w/o Energy (1.2% of total Invest-ment)(2012 MEUR / year	Annual OnM w/o Energy (2012EUR /(m^3) / m)	Coefficient of Energy (kWh / m^3)
Alto Duero - Bolarque	24	62.21	135.00	99915	845.28	746.50	260.89	1.01E-04	10.14	1.01E-07	0.8
Alto Duero - Bolarque	30	77.76	135.00	117029	990.07	933.12	244.46	9.43E-05	11.88	9.43E-08	0.8
Alto Duero - Bolarque	35	90.72	135.00	130306	1102.39	1088.64	233.31	9.00E-05	13.23	9.00E-08	0.8
Jarama - Bolarque	2.5	6.48	117.37	16714	141.4	77.76	481.92	1.86E-04	1.70	1.86E-07	0.7
Jarama - Bolarque	5	12.96	117.37	19960	168.86	155.52	287.75	1.11E-04	2.03	1.11E-07	0.7
Jarama - Bolarque	7.5	19.44	117.37	23047	194.98	233.28	221.51	8.55E-05	2.34	8.55E-08	0.7
Jarama - Bolarque	10	25.92	117.37	26092	220.74	311.04	188.08	7.26E-05	2.65	7.26E-08	0.7
Jarama - Bolarque	20	51.84	117.37	38308	324.09	622.08	138.07	5.33E-05	3.89	5.33E-08	0.6
Jarama - Bolarque	35	90.72	117.37	54584	461.78	1088.64	112.42	4.34E-05	5.54	4.34E-08	0.6
Average							0.00	1.09E-04		1.13E-07	0.86

8.6 Energy Consumption

Energy consumption required to move water between two points mainly depends on the cummulative elevation change that the water has to be lifted through [85, 86]. Some energy is also spent in overcoming internal friction within the pipeline. The cummulative elevation gain in turn depends on the pipeline routing. As pointed out in Stillwell (2010) [85] the shortest distance using a straight line approach may be considered with the possibility of giving the least energy consumption, however, this would be impractical from a property rights perspective and instead pipeline routing is more likely to follow existing rights of way such as major road networks. Some of the major urban aglomerations in each river basin are shown in Figure 8.6 and Figure 8.7, from 2009 data from the ministry of the environment [87]. It is clear that other municipalities and routes could also be chosen, but the current selection are used as possible examples. For a particular inter-basin transfer route different from these a similar analysis would be carried out. A matrix showing possible adjacent interbasin transfers through selected urban centers is shown in Table 8.9. It is assumed that these routes can be connected to offer longer distance transfers between non-adjacent basins.

The distance and elevation gains along the route is then calculated using GIS software [88] as shown in Figure 8.7. Using this methodology a matrix for each interconnection showing the distance between transfer routes is shown in Table 8.10. Table 8.11 shows the cummulative elevation gains (m) and Table 8.12 shows the net elevation changes between the selected locations. The cummulative elevation gains are used to estimate the maximum energy (kWh/m^3) needed to transfer water across the selected route as shown in Table 8.13. The net gains are used for a low end estimate of the energy needed (kWh/m^3), in which it is assumed that full energy is recovered on the downhill portions. This low estimate is shown in Table 8.14 The average value between the two is used as the final estimate for the energy (kWh/m^3) needed to overcome gravity in the long-distance interbasin transfers and is shown in Table 8.15.

The energy consumption is then calculated using the Equation 8.6.1 [85] for overcoming gravity in long distance transfers and Equation 8.6.2 [85] for the Darcy-Weisbach turbulent flow energy consumption. In Equation 8.6.1, $\frac{\Delta Ep}{\Delta t}$ is the change in potential energy in Joules per unit time, p is the fluid density, Q is the flow rate, g is acceleration due to gravity and Δh is the net or cummulative change in height. In Equation 8.6.2, h_f is the head loss due to friction, f is the friction factor, v is the average fluid velocity, ΔL is the pipe length and D is the inside pipe diameter. Parameter values were taken from the study by Stillwell 2010 [85] as shown in Table 8.8.

$$\frac{\Delta Ep}{\Delta t} = \rho Q g \Delta h \tag{8.6.1}$$

$$h_f = f \frac{v^2}{2g} \frac{\Delta L}{D} \tag{8.6.2}$$

Figure 8.6: Selected urban aglomerations with populations greater than 50,000 (data from the Ministry of the Environment 2009 [87])

The head losses due to friction using Equation 8.6.2 are shown in Table 8.19 and the corresponding energy required is shown in Table 8.17. Not all the water transfers are designed to flow through pipes so the friction value may not apply to different sections (for example in open canals). The energy needed due to friction is a small percentage (about 0.1 %) of the total, so it does not effect the results significantly. Including high flow pump efficiencies of 65% we get the final energy required for the different inter-basin transfer sections as 100/65 times the sum of the average energy to overcome gravity Table 8.15 and the energy required to overcome friction Table 8.17. This final value is shown in Table 8.18.

The average energy for different transfer sections in the National Hydrological Plan is given at about 1 kWh/m^3 [82], while Mu*ñ*oz 2010 [89] gives a range of 2.5 kWh/m^3 to 3 kWh/m^3 for the Ebro river transfer. For the sections along the Ebro river transfer project (Ebro-Jucar-Segura-Andalucia) we have an average energy consumption of (3.59+3.44+5.52)/3 = 4.2 kWh/m^3 when only considering energy to overcome gravity and (5.55+5.31+8.52)/3 = 6.5 kWh/m^3 when considering gravity, friction and pump efficiency. The higher energy values are most likely due to the paths chosen in the analysis, using urban aglomerations not located on the optimal Ebro River Transfer project path, which is more likely to be shorter and along the coast.

Table 8.7: Urban aglomerations greater than 50,000 [87]

Basin	Province	Municipality	Pop
CantbrOc	Asturias	Oviedo	189,400
CantbrOr	Gipuzkoa	San Sebastian	294,200
CICat	Barcelona	Prat de Llobregat	1,206,300
CMedAndlz	Malaga	Malaga	413,766
Duero	Valladolid	Valladolid	341,400
Ebro	Huesca	Huesca	46,500
GalCosta	ACoruna	ACoruna	310,100
GuadBarbte	Cadiz	Cadiz	247,390
Guadlqvir	Cordoba	Cordoba	301,210
Guadiana	Ciudad Real	Ciudad Real	70,400
Jucar	Valencia	Xirivella	174,600
MinoSil	Ourense	Ourense	110,100
Segura	Murcia	Murcia	270,700
Tajo	Madrid	Madrid	1,250,000
TintOdPdra	Huelva	Huelva	143,694

Table 8.8: Parameters for inter-basin transfers (Stillwell 2010 [85])

Parameter	Value	Units
Acceleration due to gravity, g	9.81	m/s^2
Density, ρ	997.08	kg/m^3
Flow rate, Q	0.8763	m^3/s
Friction factor, f	0.0115	unitless
Pipe diameter, D	3.66	m
Velocity, v	0.305	m/s
Viscosity, μ	8.94E-04	kg/m-s

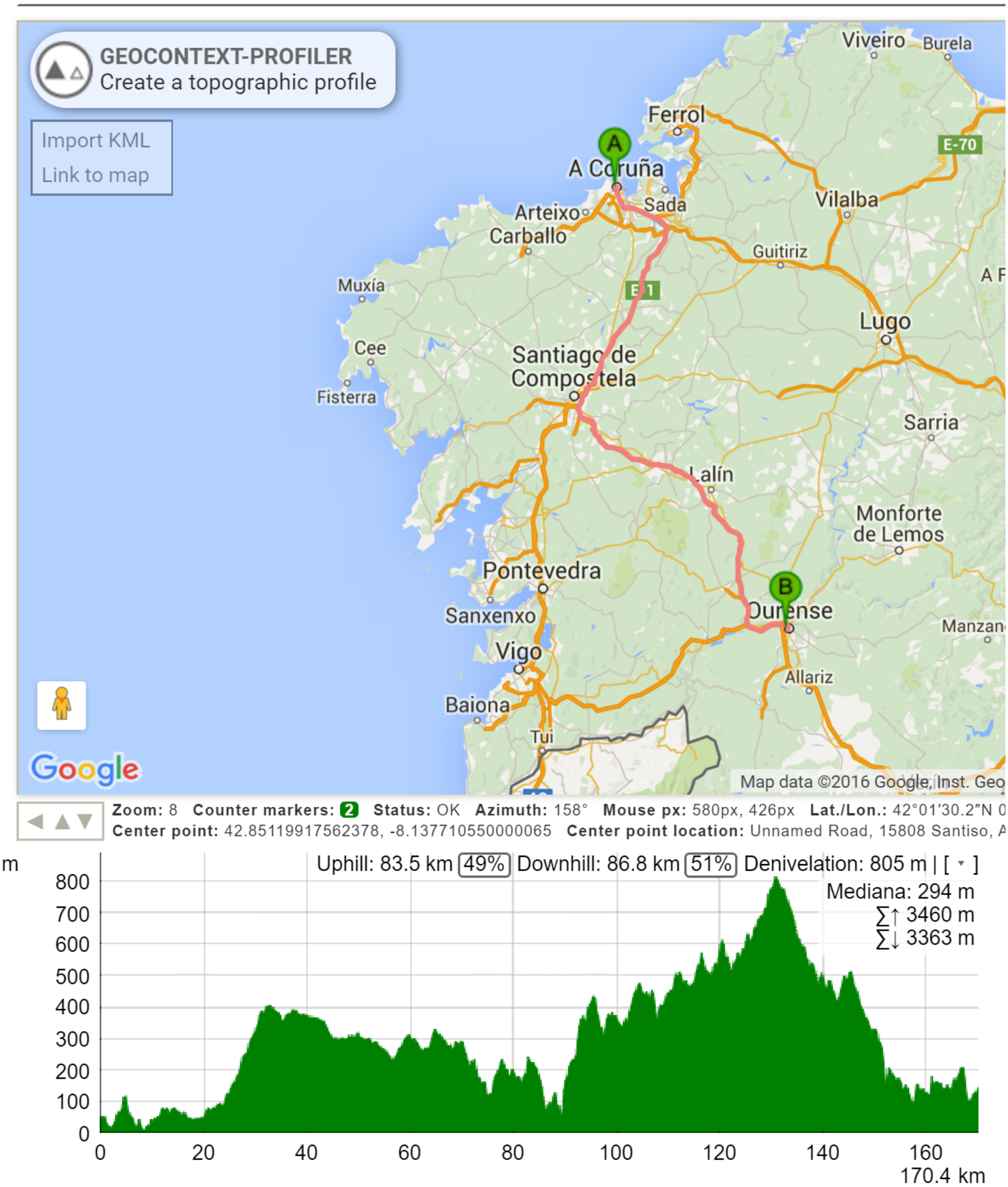

Figure 8.7: Water transfer potential route from Galicia to Mino-Sil [88]

Table 8.9: Interbasin routes through selected urban centers

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	A Coruña to Ourense	A Coruña to Oviedo	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	Ourense to A Coruña	-	Ourense to Oviedo	-	Ourense to Valladolid	-	-	-	-	-	-	-	-	-	-
CantbrOr	Oviedo to A Coruña	Oviedo to Ourense	-	Oviedo to San Sebastian	Oviedo to Valladolid	-	-	-	-	-	-	-	-	Oviedo to Huesca	-
Duero	-	-	San Sebastian to Oviedo	-	-	-	-	-	-	-	-	-	-	San Sebastian to Huesca	-
Tajo	-	Valladolid to Ourense	Valladolid to Oviedo	-	-	Valladolid to Madrid	-	-	-	-	-	-	-	Valladolid to Huesca	-
Guadiana	-	-	-	-	Madrid to Valldolid	-	Madrid to Ciudad Real	-	-	-	-	-	Madrid to Xirivella	Madrid to Huesca	-
TintOdPdra	-	-	-	-	-	Ciudad Real to Madrid	-	Ciudad Real to Huelva	Ciudad Real to Cordoba	-	-	-	Ciudad Real to Xirivella	-	-
Guadlqvir	-	-	-	-	-	-	Huelva to Ciudad Real	-	Huelva to Cordoba	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	Cordoba to Ciudad Real	Cordoba to Huelva	-	Cordoba to Cadiz	Cordoba to Malaga	Cordoba to Murcia	Cordoba to Xirivella	-	-
CMedAndlz	-	-	-	-	-	-	-	-	Cadiz to Cordoba	-	Cadiz to Malaga	-	-	-	-
Segura	-	-	-	-	-	-	-	-	Malaga to Cordoba	Malaga to Cadiz	-	Malaga to Murcia	-	-	-
Jucar	-	-	-	-	-	-	Murcia to Ciudad Real	-	Murcia to Cordoba	-	Murcia to Malaga	-	Murcia to Xirivella	-	-
Ebro	-	-	-	-	-	Xirivella to Madrid	Xirivella to Ciudad Real	-	Xirivella to Cordoba	-	-	Xirivella to Murcia	-	Xirivella to Huesca	Xirivella to Prat de Llobregat
CICat	-	-	Huesca to Oviedo	Huesca to San Sebastian	Huesca to Valladolid	Huesca to Madrid	-	-	-	-	-	-	Huesca to Xirivella	-	Huesca to Prat de Llobregat
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	Prat de Llobregat to Xirivella	Prat de Llobregat to Huesca	-

Table 8.10: Interbasin transfer route distances (km)

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	170.4	277.8	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	171.5	-	333.9	-	339.5	-	-	-	-	-	-	-	-	-	-
CantbrOr	278.8	312.5	-	362.2	250.2	-	-	-	-	-	-	-	-	621.5	-
Duero	-	-	362.1	-	-	-	-	-	-	-	-	-	-	237.4	-
Tajo	-	340.6	249.7	-	-	187.9	-	-	-	-	-	-	-	478.1	-
Guadiana	-	-	-	-	189.1	-	206.8	-	-	-	-	-	346.8	374.3	-
TintOdPdra	-	-	-	-	-	209.5	-	406.7	189.3	-	-	-	342.8	-	-

Table 8.10: Interbasin transfer route distances (km)

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
Guadlqvir	-	-	-	-	-	-	408.1	-	232.4	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	187.9	231.1	-	256.8	156.3	461.9	504.7	-	-
CMedAndlz	-	-	-	-	-	-	-	-	257.3	-	228.7	-	-	-	-
Segura	-	-	-	-	-	-	-	-	156.4	230.4	-	387.7	-	-	-
Jucar	-	-	-	-	-	-	-	-	461.6	-	387.3	-	228.4	-	-
Ebro	-	-	-	-	-	344.6	346.9	-	506.3	-	-	233.3	-	389.1	344.5
CICat	-	-	619.9	238.3	478.7	375.6	-	-	-	-	-	-	386.9	-	258.9
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	342.1	260.3	-

Table 8.11: Interbasin transfer route cummulative elevation gains (m)

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	3460	4967	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	3228	-	5676	-	3767	-	-	-	-	-	-	-	-	-	-
CantbrOr	4799	5034	-	6556	3494	-	-	-	-	-	-	-	-	6129	-
Duero	-	-	5917	-	-	-	-	-	-	-	-	-	-	4031	-
Tajo	-	3255	3043	-	-	1564	-	-	-	-	-	-	-	2269	-
Guadiana	-	-	-	-	1640	-	990	-	-	-	-	-	2758	3052	-
TintOdPdra	-	-	-	-	-	1004	-	2816	1844	-	-	-	1571	-	-
Guadlqvir	-	-	-	-	-	-	3273	-	1574	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	2317	1510	-	1235	2182	4651	3025	-	-
CMedAndlz	-	-	-	-	-	-	-	-	1352	-	3099	-	-	-	-
Segura	-	-	-	-	-	-	-	-	2355	3077	-	4019	-	-	-
Jucar	-	-	-	-	-	-	-	-	4577	-	4064	-	1787	-	-
Ebro	-	-	-	-	-	3388	2158	-	3069	-	-	2511	-	3164	2323
CICat	-	-	5518	3723	2470	3242	-	-	-	-	-	-	2638	-	2314
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	2399	2801	-

Table 8.12: Interbasin transfer route net elevation changes (m)

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	85	185	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	-85	-	121	-	559	-	-	-	-	-	-	-	-	-	-
CantbrOr	-185	-121	-	-234	466	-	-	-	-	-	-	-	-	220	-
Duero	-	-	234	-	-	-	-	-	-	-	-	-	-	452	-
Tajo	-	-559	-466	-	-	-54	-	-	-	-	-	-	-	-246	-
Guadiana	-	-	-	-	54	-	-10	-	-	-	-	-	-617	-195	-
TintOdPdra	-	-	-	-	-	10	-	-603	-506	-	-	-	-602	-	-
Guadlqvir	-	-	-	-	-	-	603	-	104	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	506	-104	-	-113	-115	-54	-95	-	-
CMedAndlz	-	-	-	-	-	-	-	-	113	-	1	-	-	-	-
Segura	-	-	-	-	-	-	-	-	115	-1	-	32	-	-	-

Table 8.12: Interbasin transfer route net elevation changes (m)

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
Jucar	-	-	-	-	-	-	-	-	54	-	-32	-	-18	-	-
Ebro	-	-	-	-	-	617	602	-	95	-	-	18	-	421	-30
CICat	-	-	-220	-452	246	195	-	-	-	-	-	-	-421	-	-451
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	30	451	-

Table 8.13: Interbasin transfer maximum energy estimate(KWh/m^3) from cummulative elevation gain

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	9.4	13.5	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	8.77	-	15.42	-	10.24	-	-	-	-	-	-	-	-	-	-
CantbrOr	13.04	13.68	-	17.81	9.49	-	-	-	-	-	-	-	-	16.65	-
Duero	-	-	16.08	-	-	-	-	-	-	-	-	-	-	10.95	-
Tajo	-	8.84	8.27	-	-	4.25	-	-	-	-	-	-	-	6.16	-
Guadiana	-	-	-	-	4.46	-	2.69	-	-	-	-	-	7.49	8.29	-
TintOdPdra	-	-	-	-	-	2.73	-	7.65	5.01	-	-	-	4.27	-	-
Guadlqvir	-	-	-	-	-	-	8.89	-	4.28	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	6.3	4.1	-	3.36	5.93	12.64	8.22	-	-
CMedAndlz	-	-	-	-	-	-	-	-	3.67	-	8.42	-	-	-	-
Segura	-	-	-	-	-	-	-	-	6.4	8.36	-	10.92	-	-	-
Jucar	-	-	-	-	-	-	-	-	12.44	-	11.04	-	4.86	-	-
Ebro	-	-	-	-	-	9.21	5.86	-	8.34	-	-	6.82	-	8.6	6.31
CICat	-	-	14.99	10.12	6.71	8.81	-	-	-	-	-	-	7.17	-	6.23
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	6.52	7.61	-

Notes:
1: Equation 8.6.1 and parameters from Table 8.8 are used to calculate the Energy per unit time in Joules/s and is converted to kWh/s by dividing by 3,600,000.
2: Q is taken as 1 m^3/sec to get kWh/m^3 (kWh/s divided by 1 m^3/s)

Table 8.14: Interbasin transfer low energy estimate (KWh/m^3) from net elevation gain

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	0.23	0.5	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	0	-	0.33	-	1.52	-	-	-	-	-	-	-	-	-	-
CantbrOr	0	0	-	0	1.27	-	-	-	-	-	-	-	-	0.6	-
Duero	-	-	0.64	-	-	-	-	-	-	-	-	-	-	1.23	-
Tajo	-	0	0	-	-	0	-	-	-	-	-	-	-	0	-
Guadiana	-	-	-	-	0.15	-	0	-	-	-	-	-	0	0	-
TintOdPdra	-	-	-	-	-	0.03	-	0	0	-	-	-	0	-	-
Guadlqvir	-	-	-	-	-	-	1.64	-	0.28	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	1.37	0	-	0	0	0	0	-	-
CMedAndlz	-	-	-	-	-	-	-	-	0.31	-	0	-	-	-	-
Segura	-	-	-	-	-	-	-	-	0.31	0	-	0.09	-	-	-
Jucar	-	-	-	-	-	-	-	-	0.15	-	0	-	0	-	-

Table 8.14: Interbasin transfer low energy estimate (KWh/m^3) from net elevation gain

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
Ebro	-	-	-	-	-	1.68	1.64	-	0.26	-	-	0.05	-	1.14	0
CICat	-	-	0	0	0.67	0.53	-	-	-	-	-	-	0	-	0
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	0.08	1.23	-

Table 8.15: Interbasin transfer average energy estimate (KWh/m^3) from net and cummulative elevation gain

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	4.82	7	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	4.39	-	7.88	-	5.88	-	-	-	-	-	-	-	-	-	-
CantbrOr	6.52	6.84	-	8.91	5.38	-	-	-	-	-	-	-	-	8.63	-
Duero	-	-	8.36	-	-	-	-	-	-	-	-	-	-	6.09	-
Tajo	-	4.42	4.14	-	-	2.13	-	-	-	-	-	-	-	3.08	-
Guadiana	-	-	-	-	2.31	-	1.35	-	-	-	-	-	3.75	4.15	-
TintOdPdra	-	-	-	-	-	1.38	-	3.83	2.51	-	-	-	2.14	-	-
Guadlqvir	-	-	-	-	-	-	5.27	-	2.28	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	3.84	2.05	-	1.68	2.97	6.32	4.11	-	-
CMedAndlz	-	-	-	-	-	-	-	-	1.99	-	4.21	-	-	-	-
Segura	-	-	-	-	-	-	-	-	3.36	4.18	-	5.51	-	-	-
Jucar	-	-	-	-	-	-	-	-	6.3	-	5.52	-	2.43	-	-
Ebro	-	-	-	-	-	5.45	3.75	-	4.3	-	-	3.44	-	4.87	3.16
CICat	-	-	7.5	5.06	3.69	4.67	-	-	-	-	-	-	3.59	-	3.15
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	3.3	4.42	-

Table 8.16: Interbasin transfer head loss (m) due to friction

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	2.54	4.14	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	2.55	-	4.97	-	5.06	-	-	-	-	-	-	-	-	-	-
CantbrOr	4.15	4.66	-	5.4	3.73	-	-	-	-	-	-	-	-	9.26	-
Duero	-	-	5.39	-	-	-	-	-	-	-	-	-	-	3.54	-
Tajo	-	5.07	3.72	-	-	2.8	-	-	-	-	-	-	-	7.12	-
Guadiana	-	-	-	-	2.82	-	3.08	-	-	-	-	-	5.17	5.58	-
TintOdPdra	-	-	-	-	-	3.12	-	6.06	2.82	-	-	-	5.11	-	-
Guadlqvir	-	-	-	-	-	-	6.08	-	3.46	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	2.8	3.44	-	3.83	2.33	6.88	7.52	-	-
CMedAndlz	-	-	-	-	-	-	-	-	3.83	-	3.41	-	-	-	-
Segura	-	-	-	-	-	-	-	-	2.33	3.43	-	5.78	-	-	-
Jucar	-	-	-	-	-	-	-	-	6.88	-	5.77	-	3.4	-	-
Ebro	-	-	-	-	-	5.13	5.17	-	7.54	-	-	3.48	-	5.8	5.13
CICat	-	-	9.24	3.55	7.13	5.6	-	-	-	-	-	-	5.76	-	3.86
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	5.1	3.88	-

Notes:
1: Equation 8.6.2 and parameters from Table 8.8 are used to calculate the head loss in meters.

Table 8.17: Interbasin transfer average energy estimate (KWh/m^3) to over come friction

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	0.01	0.01	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	0.01	-	0.01	-	0.01	-	-	-	-	-	-	-	-	-	-
CantbrOr	0.01	0.01	-	0.01	0.01	-	-	-	-	-	-	-	-	0.03	-
Duero	-	-	0.01	-	-	-	-	-	-	-	-	-	-	0.01	-
Tajo	-	0.01	0.01	-	-	0.01	-	-	-	-	-	-	-	0.02	-
Guadiana	-	-	-	-	0.01	-	0.01	-	-	-	-	-	0.01	0.02	-
TintOdPdra	-	-	-	-	-	0.01	-	0.02	0.01	-	-	-	0.01	-	-
Guadlqvir	-	-	-	-	-	-	0.02	-	0.01	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	0.01	0.01	-	0.01	0.01	0.02	0.02	-	-
CMedAndlz	-	-	-	-	-	-	-	-	0.01	-	0.01	-	-	-	-
Segura	-	-	-	-	-	-	-	-	0.01	0.01	-	0.02	-	-	-
Jucar	-	-	-	-	-	-	-	-	0.02	-	0.02	-	0.01	-	-
Ebro	-	-	-	-	-	0.01	0.01	-	0.02	-	-	0.01	-	0.02	0.01
CICat	-	-	0.03	0.01	0.02	0.02	-	-	-	-	-	-	0.02	-	0.01
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	0.01	0.01	-

Table 8.18: Interbasin transfer energy estimate (KWh/m^3) using a pump efficiency of 65% and the sum of the average energy required to overcome gravity and the energy required to overcome friction

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	7.43	10.78	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	6.77	-	12.14	-	9.06	-	-	-	-	-	-	-	-	-	-
CantbrOr	10.05	10.54	-	13.72	8.29	-	-	-	-	-	-	-	-	13.32	-
Duero	-	-	12.88	-	-	-	-	-	-	-	-	-	-	9.38	-
Tajo	-	6.82	6.38	-	-	3.29	-	-	-	-	-	-	-	4.77	-
Guadiana	-	-	-	-	3.57	-	2.09	-	-	-	-	-	5.78	6.42	-
TintOdPdra	-	-	-	-	-	2.14	-	5.92	3.88	-	-	-	3.31	-	-
Guadlqvir	-	-	-	-	-	-	8.14	-	3.52	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	5.92	3.17	-	2.6	4.58	9.75	6.35	-	-
CMedAndlz	-	-	-	-	-	-	-	-	3.08	-	6.49	-	-	-	-
Segura	-	-	-	-	-	-	-	-	5.18	6.45	-	8.51	-	-	-
Jucar	-	-	-	-	-	-	-	-	9.72	-	8.52	-	3.75	-	-
Ebro	-	-	-	-	-	8.4	5.78	-	6.65	-	-	5.31	-	7.52	4.83
CICat	-	-	11.58	7.8	5.71	7.22	-	-	-	-	-	-	5.55	-	4.86
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	5.09	6.82	-

8.7 Water Efficiency

Water losses in water transfer systems are a significant problem the world over. Water losses can occur due to leakages and theft in pipelines as well as from evaporation in open canals. In the 1990's the International Water Agency (IWA) established the Water Loss Task Force and standardized the terminology for water losses and non-revenue water as shown in Figure 8.8 [90]. The European Environment Agency (EEA) [91] estimates European water losses in urban water networks as high as 50% for Bulgaria, about 22% for Spain and as low as 5% for Germany. The Asian Development Bank [92] estimates water losses in Asia, from 25% in East Asia to 40% in Central and West Asia.

Water losses will depend heavily on the local conditions, age, components and maintenance of the transfer system and a rough estimate of 25% is used for Spain.

<table>
<tr><td rowspan="10">System input volume Q_I</td><td rowspan="5">Authorised consumption Q_A</td><td rowspan="3">Billed authorised consumption Q_{BA}</td><td>Billed water exported</td><td rowspan="3">Revenue water</td></tr>
<tr><td>Billed metered consumption</td></tr>
<tr><td>Billed unmetered consumption</td></tr>
<tr><td rowspan="2">Unbilled authorised consumption Q_{UA}</td><td>Unbilled metered consumption</td><td rowspan="7">Non-revenue water</td></tr>
<tr><td>Unbilled unmetered consumption</td></tr>
<tr><td rowspan="5">Water losses Q_L</td><td rowspan="2">Apparent losses Q_{AL}</td><td>Unauthorised consumption</td></tr>
<tr><td>Customer meter inaccuracies and data handling errors</td></tr>
<tr><td rowspan="3">Real losses Q_{RL}</td><td>Leakage on transmission and distribution mains</td></tr>
<tr><td>Leakage and overflows at storage tanks</td></tr>
<tr><td>Leakage on service connections up to point of customer meter</td></tr>
</table>

Figure 8.8: Standard terminology for water losses and non-revenue water [90]

8.8 Existing Capacity

The principal inter-basin transfers recorded in the White Book of Water in 2000 [33] are shown in Figure 8.9. More recently, Hernandez 2014 [81] summarized the existing and proposed water transfers in Spain as shown in Figure 8.10 from their study. Based on these studies the existing inter-basin capacity is estimated as shown in Table 8.19. As seen in the table, the original values of total transfers of 588 hm^3 from the White Book 2000 are the same with an additional 50 hm^3 for the Negratin-Almanzora (Guadalquivir to Anadalucia) transfer.

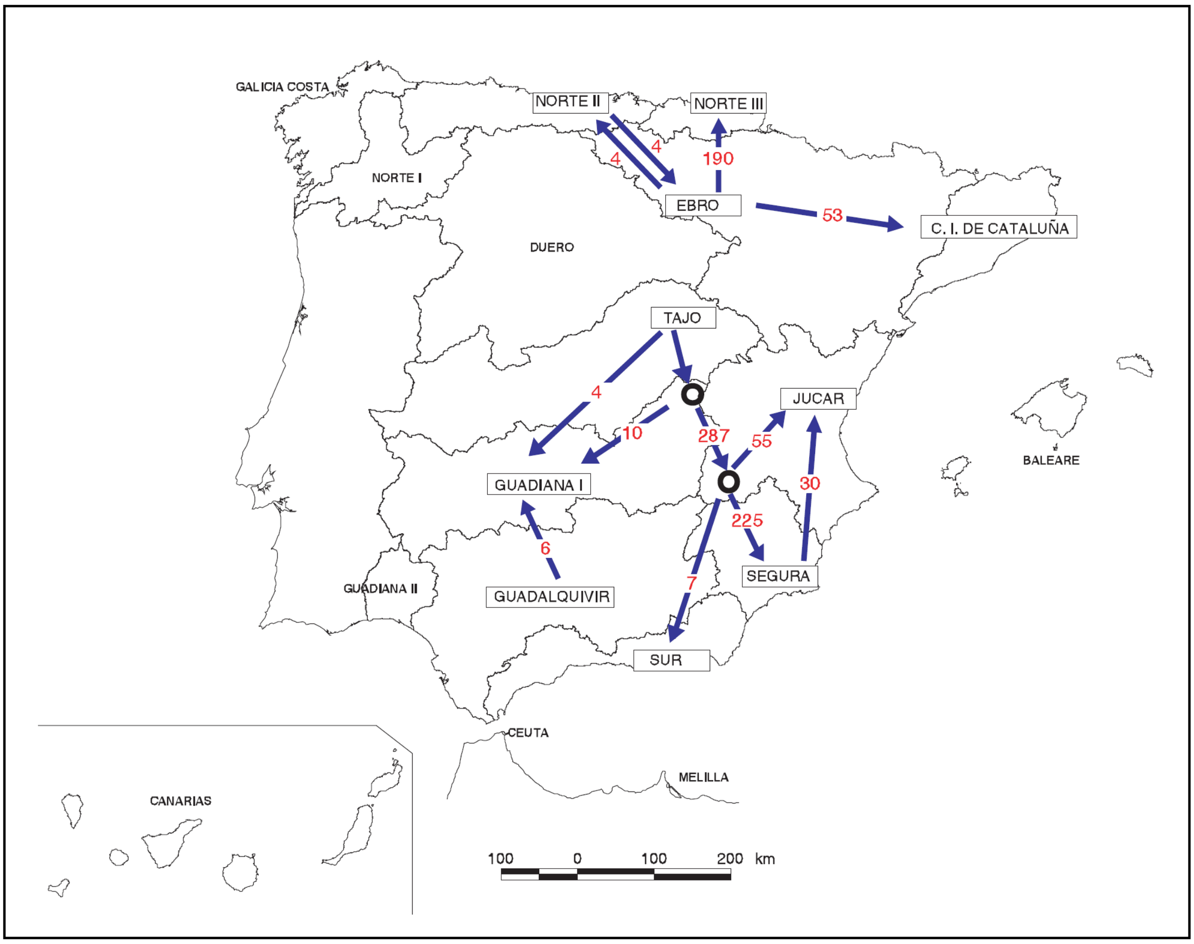

Figure 8.9: Existing inter-basin water transfer capacity (from the White Book of Water 2000 [33]

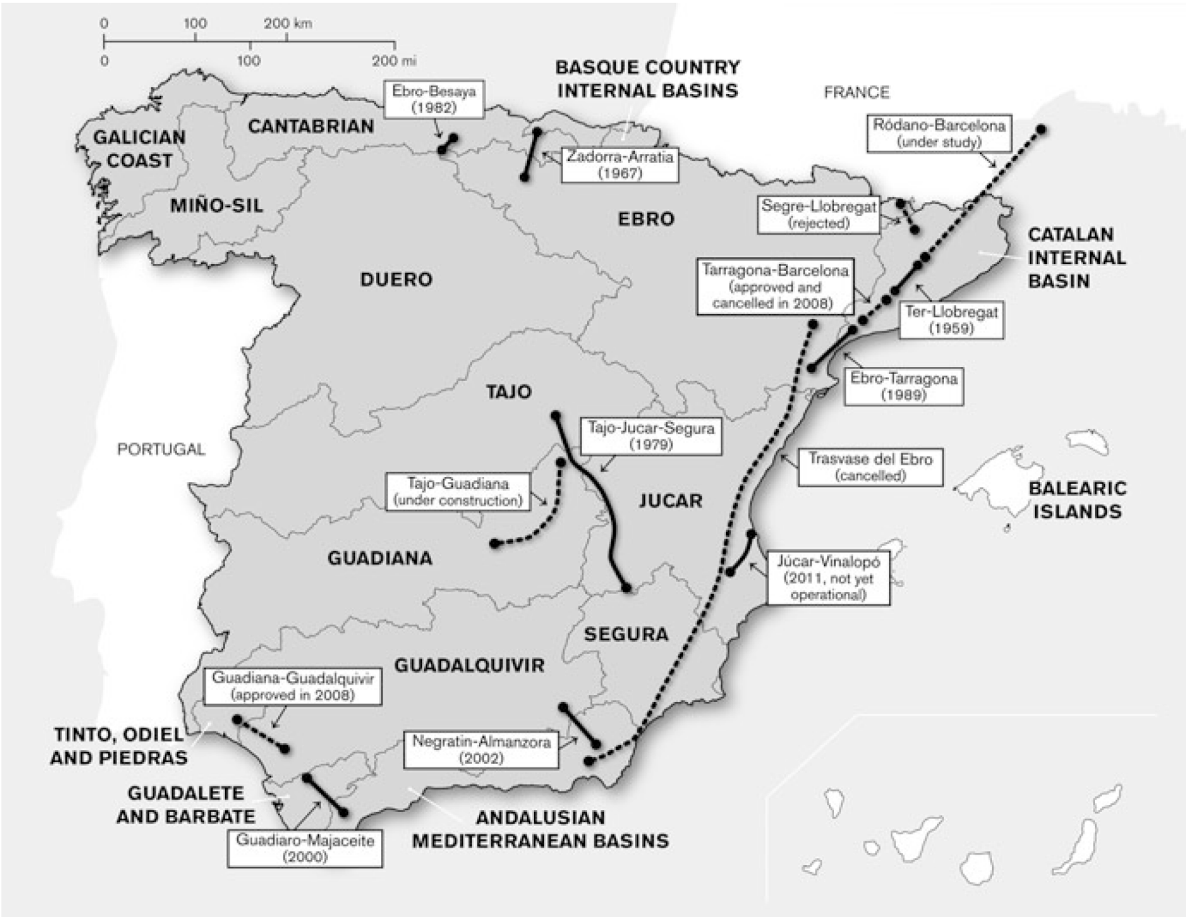

Figure 8.10: Existing inter-basin water transfer capacity (from the Hernandez 2014 [81]

Table 8.19: Interbasin transfer head loss (m) due to friction [81, 33]

	MinoSil	CantbrOc	CantbrOr	Duero	Tajo	Guadiana	TintOdPdra	Guadlqvir	GuadBarbte	CMedAndlz	Segura	Jucar	Ebro	CICat	GalCosta
MinoSil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOc	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CantbrOr	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-
Duero	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tajo	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Guadiana	-	-	-	-	-	-	14	-	-	-	7	225	55	-	-
TintOdPdra	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Guadlqvir	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GuadBarbte	-	-	-	-	-	-	6	-	-	-	50	-	-	-	-
CMedAndlz	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Segura	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jucar	-	-	-	-	-	-	-	-	-	-	-	-	30	-	-
Ebro	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CICat	-	-	4	190	-	-	-	-	-	-	-	-	-	-	53
GalCosta	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

8.9 Future Predictions and Climate Change

Climate change will impact water resources unevenly across Spain. A study from 2012 by CEDEX [93] shows the estimated changes in available water resources in different basins for two different Intergovernmental Panel on Climate Change (IPCC) scenarios [94], A2 and B2. The study uses different models corresponding to different regionalizations. The results of two of the models ECHAM4-FIC and CGCM2-FIC are shown in Table 8.20. As seen in the table the changes can be significant and this will increase the existing disparity between basin water resources.

Table 8.20: CEDEX 2012 estimates for changes in available water resources for different river basins for different IPCC climate change scenarios (A2, B2) [93, 94]

	Basin	A2i CGCM2	A2ii ECHAM4	B2i CGCM2	B2ii ECHAM4
1	GalCosta	-14	-37	-6	-34
2	MinoSil	-11	-28	-13	-37
3	CantbrOc	-20	-38	-20	-36
4	CantbrOr	-11	-34	-12	-33
5	Duero	-10	-37	-11	-30
6	Tajo	-13	-50	-11	-25
7	Guadiana	-19	-58	-16	-23
8	TintOdPdra	-8	-65	-12	-44
9	Guadaluquivir	-7	-55	-5	-36
10	GuadBarbte	-12	-56	-10	-35
11	CMedAndlz	-13	-41	-4	-31
12	Segura	-11	-44	-12	-32
13	Jucar	-11	-32	-12	-24
14	Ebro	-14	-27	-9	-26
15	CICat	-5	-11	-5	1

Chapter 9

Local Water Supply

This section describes the assumptions made to calculate the costs, water losses, energy consumption and existing capacity for the water distribution system.

9.1 Key Points

- Distribution system can be very complicated and difficult to maintain given the age, locations, material and conditions of underground and exposed piping systems
- Distirbution system can have considerable water losses from non-revenue water as a result of leaks, evaporation and illegal extractions
- Energy use for pumping can vary considerably and depends on the percentage of gravity fed water distirbution in the system

9.2 Introduction

Various sources were used to estimate the different parameters (Costs [74] [91] [95], losses [90] [96] [92], energy [97] [89] [98] [82] [99] [100], other [101] [102]. The distribution system can be very complicated with netowrks of aging and more recent pipelines in different conditions, with different water loss parameters. The required energy for pumping water also depends on the cumulative elevation gains across the system. Given, these uncertainties and differences very rough estimates were made for the systems for each basin.

9.3 Parameter Summary

Parameters for the water distribution system are summarized in Table 9.1 below.

Table 9.1: Parameter summary for water distribution

Parameter	Units	Value
Energy Consumption	(kWh/m^3)	0.38
Water Loss	(%)	25
OnM Costs	(€/m^3)	0.33
Lifetime	(Years)	25
Interest Rate	(%)	4
Investment Costs	(€/m^3)	0.26

9.4 Worked Example

A simple example to show the use of the parameters.

- Basin X has a capacity of 3 hm^3 installed
- Water needed for the year is 6 hm^3
- Water losses are 25% so water needed is 6 x 100/75 = 8 hm^3
- Water losses will be = 8 x 25/100 = 2 hm^3
- Energy consumption will be = 8 x 10^6 m^3 x 0.38 kWh/m^3 x 10^{-6} GWh/kWh = 3 GWh
- O&M costs = 8 x 10^6 m^3 x 0.33 €/m^3 x 10^{-6} M€/€= 2.64 Million €
- Investment Cost = 3 x 10^6 m^3 x 0.26 €/m^3 x 10^{-6} M€/€= 0.78 Million €

9.5 Costs

The full cost of water is composed of several components as shown in Figure 9.1 [74]. This section deals only with the full supply costs. The 2007 report [95] by the ministry of the environment summarizes the costs associated with several different water services in Spain. These are divided into surface water collection, subsurface water collection, urban water supply, municipal sewage collection, sewage treatment, distirbution of agricultural water and discharge control. This same distribution of costs is used in the analysis of the recuperation of costs in the individual river basin plans for the cycle 2015-2021 published in 2014 and 2015 [98]. The operation and maintenence as well as the investment costs associated with urban water supply are extracted from these studies for the parameters to be used for water distribution within a basin.

According to guidelines by the Ministry of the Environment the distribution of costs for different water services are aggregated as follows [98, 95].

Water Service Cost Composition

i Superficial Sources: Abstraction, impoundment, storage and supply to local distribution

ii Groundwater: Abstraction and supply to local distribution

iii Distribution for irrigation

iv Urban Supply: Water purification and local distribution

v Self service: Direct water abstraction, supply and treatment by users

vi Reuse

vii Wastewater Treatment: Treatment of municipal wastewater

The individual river basin plans [98] however, report different levels of water costs for different services, some reporting aggregated costs for all services while others disaggregating the costs according to the guidelines above. Furthermore different levels of detail on investment and operation costs are provided. Given the large range and uncertainty in data uniformity and methods, we use an average number derived from some of these studies.

A summary of the costs associated with water distribution per river basin as given in the 2007 report by the Ministry of Environment [95] is shown in Table 9.2.

Table 9.2: Water Distribution Costs

Basin	Urban Distribution (2002) M€ [95]	Urban Demand (2000) (hm^3) [33]	Costs (€/m^3)
Galicia	81.35	210	0.39
Norte (Cantabrico Occidental)	232.27	214	1.09
CI Pais Vasco (Cantabrico Oriental)	110.20	269	0.41

Table 9.2: Water Distribution Costs

Basin	Urban Distribution (2002) M€ [95]	Urban Demand (2000) (hm^3) [33]	Costs (€/m^3)
Ebro	121.95	313	0.39
CI Cataluna	341.40	682	0.50
Duero	96.00	214	0.45
Tajo	467.63	768	0.61
Jucar	239.44	563	0.43
Guadiana	121.89	119	1.02
Guadalquivir	389.04	482	0.81
Segura	98.39	172	0.57
CM Andaluzas	89.32	248	0.36
Average			0.58

The operation and investment costs for different volumes of water serviced for "Urban Supply" (residence and industry/energy) are provided for the Tajo basin in the basin hydrological plan [99]. The resulting operation costs per cubic meter as defined in the report, were considered as the aggregated costs of water treatment to make it potable, water supply and energy costs for water supply. The results are shown in Table 9.3

Table 9.3: Water Distribution Costs for the Tajo Basin

	Volume (hm^3)	Cost OnM (M€)	Cost Inv (M€)	Costs Total (M€)	Cost OnM (€/m^3)	Cost Invs (€/m^3)	Cost Total (€/m^3)
Urban	512	256.19	160.86	417.05	0.50	0.31	0.81
Indus/Energy	118	64.26	44.42	108.68	0.54	0.38	0.92
Average					0.52	0.35	0.87

The O&M costs are further disaggregated by subtracting the O&M costs of purification systems as calculated in Section 7.6. An average value of the purifying treatment methods to treat water to quality A (with desalination (0.3 €/m^3) and without desalination 0.13 €/m^3)

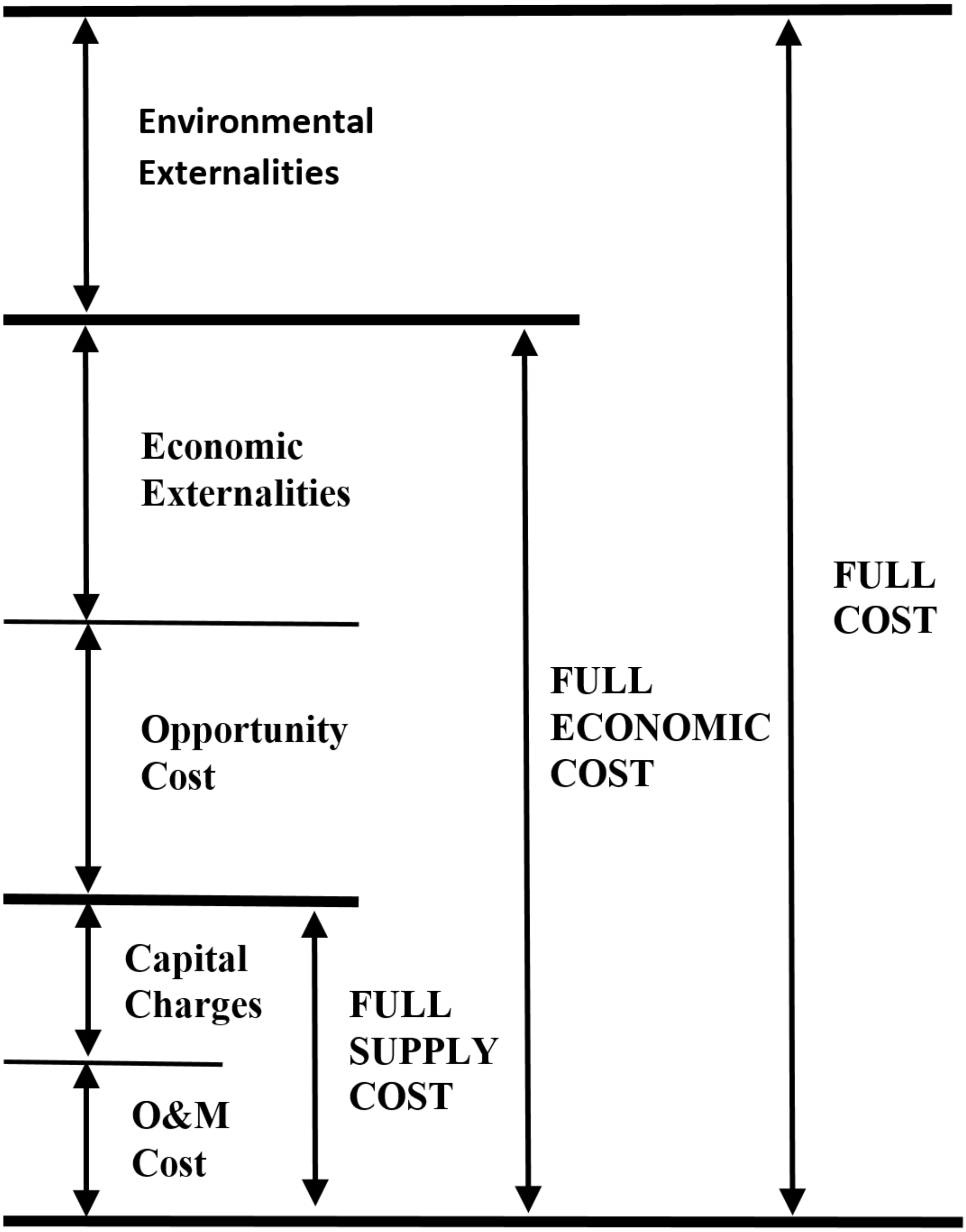

Figure 9.1: Full cost of water supply [74]

of 0.22 €/m^3 was used. Energy consumption for distribution systems was assumed at 0.38 kWh/m^3 as discussed in Section 9.6 for the year 2002. The Spanish Hydrological Plan from 2000 [82] uses an average energy cost of 8 Spanish Pesetas per kWh. Converting these to 2000 €and then accounting for inflation to 2012, we have a cost of 8 x 0.006 x 1.4 = 0.0672 €/kWh (The Spanish report on costs of water systems [95] uses a fixed value of 0.07 €/kWh) . This gives an approximate energy cost of 0.026 €/m^3 for the distribution system. Thus, we calculate an approximate O&M cost for the distribution system without purification or energy as 0.58 - 0.22 - 0.026 = 0.33 €/m^3.

For investment costs the values given for the annual amortization costs in the Tajo river Basin are used as a starting average. As alluded to in the basin hydrological plan [99] the cost is assumed to included treatment costs. Therefore the amortization costs for purification plants from Section 7.6 (interest rate 4% and lifetime of 20 years) 0.07 €/m^3 and for brackish water desalination from Section 6.6 (interest rate of 4% and lifetime of 15 years) 0.11 €/m^3 is used to get an average value for treatment processes. Thus, we calculate an approximate investment cost for distribution systems as 0.35 - 0.09 = 0.26 €/m^3.

9.6 Energy Consumption

Energy consumption basically depends on the energy required to lift and move water between two points. The energy thus depends on the sections of the transfer in which there is a positive change in height. However, at the basin scale it is too complicated to calculate the net elevation gain for individual systems and an average value per cubic meter of water is used.

In Hardy 2010 [103] a range of values for energy used in the distribution system is given from 0.064 kWh/m^3 to 0.32 kWh/m^3. Another study, Muñoz 2010 [89], estimates energy consumption in water distribution to range between 0.2 kWh/m^3 and 0.8 kWh/m^3 while for the Ebro River long distance transfer energy consumption is estimated between 2.5 kWh/m^3 to 3 kWh/m^3. A World Bank study from 2012 [97] also notes the dependency of energy consumption on the share of gravity-fed supply in the system. For surface water the study estimates 10% of total energy consumption is spent on raw water extraction, 10% on water treatment and 80% on clean water transmission and distribution. For groundwater the estimates are 30% for raw water extraction, 1% for treatment and 69% for clean water transmission and distribution. In the US study from 2004 [100] reports that there is an enormous variation in the energy consumption for the distribution system depending on the gravity-fed parts of the system as well as the amount of losses. Estimates are given ranging from 170 kWh/af (0.14 kWh/m^3) to 215 kWh/af (0.17 kWh/m^3) for the San-Diego Levy-Helix Water District total distribution system, to 430 kWh/af (0.35 kWh/m^3) for the Levy-Helix Water District electrically presuurized part of the system, to 940 kWh/af (0.76 kWh/m^3) for the San Diego North City water treatment plant distribution system. The ranges of values from the different studies are summarized in Table 9.4

Table 9.4: Energy consumption in water distribution systems

Study	Low Range (kWh/m^3)	High Range (kWh/m^3)	Average (kWh/m^3)
Hardy 2004 [103]	0.06	0.32	0.19
Muñoz 2010 [89]	0.20	0.80	0.50
Wolff 2004 [100]	0.14	0.76	0.45
Average	0.13	0.63	0.38

9.7 Water Efficiency

As discussed in Section 8.7 the European Environment Agency (EEA) [96, 91] estimates water losses in urban water networks as high as 50% for Bulgaria, about 22% for Spain and as low as 5% for Germany. The Asian Development Bank [92] estimates water losses in Asia, from 25% in East Asia to 40% in Central and West Asia. In a study from California from 2004 [100] estimates are given as varying typically between 6 % to 15 % but in some cases as high as 30 %.

Water losses will depend heavily on the local conditions, age, components and maintenance of the distribution system and a conservative estimate of 25% is used for Spain.

9.8 Existing Capacity

For lack of better data, existing distribution capacity is assumed to be double of the total end user demands for the different sectors as reported by the online digital water database of the ministry of environment [80]. The demands and resulting capacity estimation is shown in Table 9.5.

Table 9.5: Volume of Water Demands (hm^3) from the Libro Blanco Digital [80]

Basin	Urban	Industrial	Irrigation	Power Plant Cooling	Total	Capacity Estimate
GalCosta	210	53	532	24	819	1638

Table 9.5: Volume of Water Demands (hm^3) from the Libro Blanco Digital [80]

Basin	Urban	Industrial	Irrigation	Power Plant Cooling	Total	Capacity Estimate
MinoSil	77	32	475	33	617	1234
CantbrOc	214	280	55	40	589	1178
CantbrOr	269	215	2	0	486	972
Duero	214	10	3603	33	3860	7720
Tajo	768	25	1875	1397	4065	8130
Guadiana	119	31	2157	5	2312	4624
TintOdPdra	38	53	128	0	219	438
Guadaluquivir	482	80	2845	0	3407	6814
GuadBarbte	50	8	295	0	353	706
CMedAndlz	248	32	1070	0	1350	2700
Segura	172	23	1639	0	1834	3668
Jucar	563	80	2284	35	2962	5924
Ebro	313	415	6310	3340	10378	20756
CICat	682	296	371	8	1357	2714
TOTAL	4419	1633	23641	4915	34608	69216

9.9 Future Predictions and Climate Change

Climate change may impact distribution systems by increasing evaporation from open canals.

Chapter 10

Water Use Technologies

10.1 Key Points

10.2 Introduction

10.3 Parameter Summary

10.4 Worked Example

10.5 Costs

10.6 Energy Consumption

10.7 Water Efficiency

10.8 Existing Resources

As shown in Table 10.1 [27].

Table 10.1: Total and groundwater usage in Spain [27]

Sector	Total water (hm^3/yr})	Groundwater (hm^3/yr)	% Groundwater of total
Domestic Supply	5,500(15%)	1,000-1,500(20%)	20%
Irrigation	24,000(65%)	4,000-5,000(75%)	75%

Table 10.1: Total and groundwater usage in Spain [27]

Sector	Total water (hm^3/yr})	Groundwater (hm^3/yr)	% Groundwater of total
Industry	1,500(4%)	300-400(5%)	5%
Energy	6000(16%)	-	-
Total	37,500(100%)	5,500-6,500(100%)	100%

10.9 Existing Capacity

10.10 Future Predictions and Climate Change

Bibliography

[1] D. Robinson, Construction and operating costs of groundwater pumps for irrigation in the riverine plain, CSIRO Land and Water, 2002.

[2] T. Zhu, C. Ringler, X. Cai, Energy price and groundwater extraction for agriculture: exploring the energy-water-food nexus at the global and basin levels, in: International Conference of Linkages Between Energy and Water Management for Agriculture in Developing Countries, Hyderabad, India, 2007.

[3] UNEP, Rainwater harvesting and utilisation. an environmentally sound approach for sustainable urban water management: An introductory guide for decision-makers, Tech. rep., United Nations Environment Programme (UNEP) (2001).
URL http://www.unep.or.jp/ietc/publications/urban/urbanenv-2/index.asp

[4] Environment Agency, Harvesting rainwater for domestic uses: an information guide, Tech. rep., Bristol, UK (oct 2010).
URL http://webarchive.nationalarchives.gov.uk/20140328084622/http:/cdn.environment-agency.gov.uk/geho1110bten-e-e.pdf

[5] European Environment Agency (EEA), Land use - State and impacts (Spain), EEA, accessed: 2016-03-18 (2006).
URL http://www.eea.europa.eu/soer/countries/es/land-use-state-and-impacts-spain

[6] S. Ward, Rainwater harvesting in the uk–current practice and future trends, in: Young Scientists Workshop, Amsterdam, Netherlands, 2007.
URL http://www.harvesth2o.com/UK%20Rainwater%20Harvesting%20Study.pdf

[7] A. Rahman, E. Eroksuz, J. Dbais, K. Haddad, S. M. Islam, Rainwater harvesting in large residential buildings in Australia, INTECH Open Access Publisher, 2012.
URL http://cdn.intechopen.com/pdfs-wm/34605.pdf

[8] L. Domènech, D. Saurí, A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the metropolitan area of barcelona (spain): social experience, drinking water savings and economic costs, Journal of Cleaner production 19 (6) (2011) 598–608.

[9] C. Batchelor, C. Fonseca, S. Smits, Life-cycle costs of rainwater harvesting systems, Occasional paper 46.
URL http://www.ircwash.org/sites/default/files/Batchelor-2011-Lifecycle.pdf

[10] K. Keating, H. Keeble, A. Petit, D. Stark, Cost estimation for suds - summary of evidence, Tech. rep., Bristol, UK, report âĂŞSC080039/R9 (mar 2015).
URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/411509/Cost_estimation_for_SUDS.pdf

[11] CSE, How much will it cost to catcch rain?, accessed: 2016-03-18 (2016).
URL http://www.rainwaterharvesting.org/urban/costs.htm

[12] E. Hajani, A. Rahman, Reliability and cost analysis of a rainwater harvesting system in peri-urban regions of greater sydney, australia, Water 6 (4) (2014) 945–960.

[13] B. Hicks, A cost-benefit analysis of rainwater harvesting at commercial facilities in arlington county, virginia, masters Project (2008).
URL https://www.rainharvest.com/more/MastersProjectRainHarvest_200805.pdf

[14] EPA, Rainwater harvesting. conservation, credit, codes, and cost literature review and case studies, ePA-841-R-13-002 (jan 2013).
URL https://www.epa.gov/sites/production/files/2015-11/documents/rainharvesting.pdf

[15] I. F. Pèrez, Aprovechamiento de aguas pluviales, escola Politècnica superior D'edificaiò de Barcelona (jan 2009).
URL http://upcommons.upc.edu/bitstream/handle/2099.1/7222/pfc-e%202009.058%20mem%C3%B2ria.pdf

[16] J. Dbais, A. Rahman, P. Ronaldson, S. Shrestha, et al., Life cycle costing of rainwater tank as a component of water sensitive urban design, Rainwater and Urban Design 200713th International Rainwater Catchment Systems Conference.
URL http://www.eng.warwick.ac.uk/ircsa/pdf/13th/Rahman.pdf

[17] A. Rahman, J. Dbais, M. Imteaz, et al., Sustainability of rainwater harvesting systems in multistorey residential buildings, American Journal of Engineering and Applied Sciences 3 (2010) 73–82, iSSN Print: 1941-7020.
URL http://thescipub.com/PDF/ajeassp.2010.73.82.pdf

[18] R. Farreny, T. Morales-Pinzón, A. Guisasola, C. Taya, J. Rieradevall, X. Gabarrell, Roof selection for rainwater harvesting: quantity and quality assessments in spain, Water Research 45 (10) (2011) 3245–3254.

[19] A. S. Vieira, C. D. Beal, E. Ghisi, R. A. Stewart, Energy intensity of rainwater harvesting systems: A review, Renewable and Sustainable Energy Reviews 34 (2014) 225–242.

[20] C. Parkes, H. Kershaw, J. Hart, R. Sibille, Z. Grant, Energy and carbon implications of rainwater harvesting and greywater recycling, Tech. rep., report SC090018 (2010).
URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291745/scho0610bsmq-e-e.pdf

[21] Ministerio de medio ambiente, Gobierno de España, Reservas en embalses, libro digital del agua, accessed: 2016-02-08.
URL http://servicios2.magrama.es/sia/visualizacion/lda/recursos/superficiales_embalses.jsp

[22] Ministerio de medio ambiente, Gobierno de España, Descargas, embalse centro de estudios hidrogrÃąficos, accessed: 2016-02-08.
URL http://servicios2.magrama.es/sia/visualizacion/descargas/capas.jsp#EMBALSE

[23] Ministerio de medio ambiente, Gobierno de España, Descargas, serie de datos de los valores de reservas en embalse de la red roea, accessed: 2016-02-08.
URL http://servicios2.magrama.es/sia/visualizacion/descargas/series.jsp#EMBALSES

[24] Red Eléctrica de España, Publications: Statistical series, http://www.ree.es/en/publications/indicators-and-statistical-data/statistical-series, accessed: 2016-03-09.

[25] S. Grin, Geometry and area-depth-volume curves of the reservoirs in the semiarid madalena basin in northeast brazil, final Bachelor Report.
URL http://essay.utwente.nl/66590/1/Grin_Sido.pdf

[26] J. Molinero, E. Custodio, A. Sahuquillo, Groundwater in spain: Overview and management practices, Citeseer.

[27] N. Hérnandez, L. Martınez, M. Llamas, E. Custodio, Groundwater in the southern member states of the european union: An assessment of current knowledge and future prospects country report for spain (halle, germany: European academies science advisory council) (2010).

[28] M. R. Llamas, A. Garrido, Lessons from intensive groundwater use in spain: economic and social benefits and conflicts, The agricultural groundwater revolution: Opportunities and threats to development (2007) 266–298.

[29] M. R. Llamas, E. Custodio, A. de la Hera, J. Fornés, Groundwater in spain: increasing role, evolution, present and future, Environmental Earth Sciences 73 (6) (2015) 2567–2578.

[30] M. Mora, J. Vera, C. Rocamora, R. Abadia, Energy efficiency and maintenance costs of pumping systems for groundwater extraction, Water resources management 27 (12) (2013) 4395–4408.

[31] J. Roumasset, C. Wada, et al., Energy costs and the optimal use of groundwater, in: 2014 Allied Social Science Association (ASSA) Annual Meeting, January 3-5, 2014, Philadelphia, PA, Agricultural and Applied Economics Association, 2013.

[32] Ministerio de medio ambiente, Gobierno de España, Subterránea, accessed: 2016-02-08.
URL http://servicios2.magrama.es/sia/visualizacion/descargas/series.jsp#SUBTERRANEA

[33] Ministerio de medio ambiente, Gobierno de España, Libro blanco del agua en España, Secretaría de estado de aguas y costas, Madrid, Spain, 2000.

[34] Centro de Estudios y Experimentación de Obras Públicas (CEDEX), Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua,evaluación del impacto del cambio climático en los recursos hídricos en régimen natural, centro de Estudios Hidrográficos, CEDEX: 43-308-5-001 (2010).

[35] C. Fritzmann, J. Lówenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination, Desalination 216 (1) (2007) 1–76.

[36] L. Martínez-Cortina, A. Garrido, E. Lopez-Gunn, Re-thinking water and food security: fourth Botin Foundation water workshop, CRC Press, 2010.

[37] X. Bernat, O. Gibert, R. Guiu, J. Tobella, C. Campos, The economics of desalination for various uses, in: L. Martínez-Cortina, A. Garrido, E. Lopez-Gunn (Eds.), Re-thinking water and food security, CRC Press, Leiden, The Netherlands, 2010, Ch. 18, pp. 329–346.

[38] J. Olcina Cantos, E. Moltó Mantero, et al., Recursos de agua no convencionales en españa: Estado de la cuestión, 2010, Investigaciones Geografía.

[39] Hispagua, Ministerio de medio ambiente, Gobierno de España, Desalación, accessed: 2015-12-14 (2015).
URL http://hispagua.cedex.es/node/61332

[40] Instituto EspaÃśol de Comercio Exterior (ICEX, La desalinización en españa, accessed: 2015-12-14 (2007).
URL http://www.acuamed.es/media/publicaciones/desalinizacion-en-espana.pdf

[41] L. Henthorne, The current state of desalination, in: Proceedings of the International Desalination Association (IDA) World Congress, Dubai, United Arab Emirates, 2009, pp. 7–12.

[42] J. Koschikowski, Water desalination: When and where will it make sense, Fraunhofer Institute for Solar Energy Systems ISE Freiburg, Germany.

[43] Ministerio de medio ambiente, Gobierno de España, DesalaciÃşn, accessed: 2015-12-14.
URL http://servicios2.marm.es/sia/visualizacion/lda/recursos/noconvencionales_desalacion.jsp

[44] Ministerio de medio ambiente, Gobierno de España, Sistema integrado de información del agua, capacidad de desalaciÃşn por municipio, accessed: 2015-12-14 (2012). URL http://servicios2.marm.es/sia/visualizacion/descargas/mapas.jsp#var-municipio-municipio_capdesalacion

[45] A. Zander, M. Elimelech, D. Furukawa, P. Gleick, K. Herd, K. L. Jones, P. Rolchigo, S. Sethi, J. Tonner, H. J. Vaux, et al., Desalination: A national perspective, National Research Council, The National Academies.

[46] W. Harvey, Desalination efficiency: Energy, water and other resources, GE Water and Process Technologie.

[47] Encyclopedia of Desalination and Water Resources (DESWARE), Energy requirements of desalination processes, http://www.desware.net/desa4.aspx, accessed: 2015-12-24.

[48] Sidem-Veolia, Faq about desalination, http://www.sidem-desalination.com/en/Process/FAQ/, accessed: 2015-12-24.

[49] S. Al-Hengari, M. El-Bousiffi, W. El-Mudir, Performance analysis of a msf desalination unit, Desalination 182 (1) (2005) 73–85.

[50] M. Abdel-Jawad, Energy sources for coupling with desalination plants in gcc countries, Report for ESCWA.

[51] A.-M. Ibrahim, Energy consumption and performance for various desalination processes, http://faculty.ksu.edu.sa/Almutaz/Documents/Energy%20Consumption%20and%20Performance%20for%20Various%20Desalination%20Processes.pdf, accessed: 2015-12-24.

[52] K. Reddy, N. Ghaffour, Overview of the cost of desalinated water and costing methodologies, Desalination 205 (1) (2007) 340–353.

[53] J. C. Radcliffe, Water recycling in Australia: a review undertaken by the Australian academy of technological sciences and engineering, Australian Academy of Technological Sciences and Engineering, 2004.

[54] R. Mujeriego, La reutilización planificada del agua aspectos reglamentarios, sanitarios, técnicos y de gestión, Universidad Politécnica de Cataluña. Barcelona.

[55] U. EPA, Guidelines for water reuse, Washington DC: US Agency for International Development.

[56] N. R. C. U. C. on the Assessment of Water Reuse as an Approach for Meeting Future Water Supply Needs, Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater, National Academies Press, 2012.

[57] A. Fernández-Alba, S. Malato, M. Gómez-Ramos, G. Carbonell, C. Fernández-Torija, M. Porcel, F. Pro, M. Contreras, J. Crespo, C. Jacquin, et al., Ejemplos prácticos de reutilización de agua residual tratada y regenerada para el riego de cultivos. evaluación de riesgo.

[58] V. Tsiridis, A. Kougolos, A. Kotios, P. Plageras, Y. Saratsis, Wastewater reclamation and reuse, Discuss. Pap. Ser 15 (2009) 139–148.

[59] E. Ortega de Miguel, La reutilizacón de las aguas residuales depuradas en españa. perspectivas, oportunidades y barreras, Tech. rep., jornada sobre reutilizacón de aguas depuradas, Pamplona 14 de noviembre de 2008 (2008).
URL http://www.crana.org/themed/crana/files/docs/154/013/enriquecedex.pdf

[60] Centro de Estudios y Experimentación de Obras Públicas (CEDEX), Wastewater reclamation and reuse in spain, Tech. rep., 5th World water forum, Bridging divides for water, 16-22 March 2009, Istabul, Turkey (2009).
URL http://ceh-flumen64.cedex.es/5thWorldWaterForum/T3/10_WASTEWATER.pdf

[61] Centro de Estudios y Experimentación de Obras Públicas (CEDEX), Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua,efectos potenciales del cambio climático en las demandas de agua y estrategias de adaptación, centro de Estudios Hidrográficos, CEDEX: 45-407-1-001 (2012).

[62] Environmental Protection Agency (EPA), Water recyling and reuse: The environmental benefits, Tech. rep., Water Division Region IX - EPA 909-F-98-001.
URL https://www3.epa.gov/region9/water/recycling/brochure.pdf

[63] Ministerio de medio ambiente, Gobierno de España, El plan nacional de calidad de las aguas: Saneamiento y depuración 2007-2015, http://www.magrama.gob.es/

es/agua/planes-y-estrategias/PlanNacionalCalidadAguas_tcm7-29339.pdf (2007).

[64] B. Jiménez, T. Asano, Water reuse: an international survey of current practice, issues and needs, Water Intelligence Online 7 (2008) 9781780401881.

[65] T. Asano, F. Burton, H. Leverenz, R. Tsuchihashi, G. Tchobanoglous, Water reuse: Issues, technologies, and applications, McGrawHill, New York, USA.

[66] J. Wang, Human activity and the environment (16-201-x), section 4: Wastewater discharges, Tech. rep., accessed: 2016-03-08 (2012).
URL http://www.statcan.gc.ca/pub/16-201-x/2012000/part-partie4-eng.htm

[67] R. I. Esteban, E. O. de Miguel, Present and future of wastewater reuse in spain, Desalination 218 (1) (2008) 105–119.

[68] Ministerio de la Presidencia , Real decreto 1620/2007: Reutilización de las aguas depuradas, http://www.boe.es/buscar/doc.php?id=BOE-A-2007-21092, ref: BOE-A-2007-21092 (2007).

[69] Ministerio de medio ambiente, Gobierno de España, Plan nacional de reutilización de aguas (version preliminar de plan), http://www.magrama.gob.es/es/calidad-y-evaluacion-ambiental/participacion-publica/version_preliminar_pnra231210_tcm7-153069.pdf (2008).

[70] G. Rodriguez-Garcia, M. Molinos-Senante, A. Hospido, F. Hernández-Sancho, M. Moreira, G. Feijoo, Environmental and economic profile of six typologies of wastewater treatment plants, Water research 45 (18) (2011) 5997–6010.

[71] F. Hernández-Sancho, B. Lamizana-Diallo, J. Mateo-Sagasta, M. Qadir, Economic valuation of wastewater - the cost of action and the cost of no action, Tech. rep., iSBN: 978-92-807-3474-4 (2015).
URL http://unep.org/gpa/Documents/GWI/Wastewater%20Evaluation%20Report%20Mail.pdf

[72] R. Iglesias Esteban, Water reuse in spain: Data overview and costs estimation of suitable treatment trains, Tech. rep., INNOVA-MED Conference, Water reclamation and reuse, 8-9 October 2009, Girona, Spain (2009).
URL http://www.idaea.csic.es/innova-med/power%20point/Iglesias.pdf

[73] M. Molinos-Senante, F. Hernández-Sancho, R. Sala-Garrido, Cost–benefit analysis of water-reuse projects for environmental purposes: a case study for spanish wastewater treatment plants, Journal of Environmental Management 92 (12) (2011) 3091–3097.

[74] E. Cabrera, Water pricing in Spain: A case study, Fundación Botín: Water Observatory, accessed: 2016-03-18 (2012).
URL http://www.rac.es/ficheros/doc/00871.pdf

[75] El Instituto para la DiversificaciÃşn y Ahorro de la EnergÃŋa (IDAE), Consumo energético en el sector de agua, estudio de prospectiva, Ministerio de industria, turismo y comercio, Gobierno de España, accessed: 2016-03-08 (2010).
URL http://www.idae.es/uploads/documentos/documentos_Estudio_de_prospectiva_Consumo_Energetico_en_el_sector_del_agua_2010_020f8db6.pdf

[76] L. Moore, Energy use at water and wastewater treatment plants, Tech. rep., accessed: 2016-03-08 (2012).

[77] I. Caffoor, Energy efficienct water and wastewater treatment, Tech. rep. (2008).
URL www.cost.eu/download/5352

[78] International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) , Evaluation and analysis of water usage of power plants with co2 capture, Tech. rep. (2011).
URL http://hub.globalccsinstitute.com/sites/default/files/publications/101096/evaluation-analysis-water-usage-power-plants-co-capture.pdf

[79] Ministerio de medio ambiente, Gobierno de España, Depuradora asociada a aglomeración urbana, accessed: 2016-03-08 (2009).
URL http://servicios2.magrama.es/sia/visualizacion/descargas/capas.jsp

[80] Ministerio de medio ambiente, Gobierno de España, Libro blanco digital del agua en españa: Recursos no convenciales, reutilizacion, accessed: 2016-03-08 (2008).
URL http://servicios2.marm.es/sia/visualizacion/lda/recursos/noconvencionales_reutilizacion.jsp

[81] N. Hernández-Mora, L. del Moral Ituarte, F. La-Roca, A. La Calle, G. Schmidt, Interbasin water transfers in spain: Interregional conflicts and governance responses, in: Globalized Water, Springer, 2014, pp. 175–194.

[82] Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de España, Planes Hidrológicos Nacional (2000).
URL https://www.chsegura.es/chs/planificacionydma/planhidrologiconacional/phn/

[83] A. Garrido, An economic appraisal of the spanish national hydrological plan 1, International Journal of Water Resources Development 19 (3) (2003) 459–470.

[84] P. Arrojo, M. Atwi, E. Miguelez, The real cost of the transfer, Analysis and socio-economic assessment of the ebro transfers included in the Spanish National hydrological Plan, SNHP (Summary), World Wildlife Fund (2003).
URL http://assets.wwf.es/downloads/cost_transfers_ing_1.pdf

[85] A. S. Stillwell, C. W. King, M. E. Webber, Desalination and long-haul water transfer as a water supply for dallas, texas: A case study of the energy-water nexus in texas, Texas Water Journal 1 (1) (2010) 33–41.

[86] S. C. Parkinson, N. Djilali, V. Krey, O. Fricko, N. Johnson, Z. Khan, K. Sedraoui, A. H. Almasoud, Impacts of groundwater constraints on saudi arabiaâĂŹs low-carbon electricity supply strategy, Environmental science & technology 50 (4) (2016) 1653–1662.

[87] Ministerio de medio ambiente, Gobierno de España, Descargas, aglomeraciones urbanas, accessed: 2016-02-08.
URL http://servicios2.magrama.es/sia/visualizacion/descargas/mapas.jsp#tema-aauu

[88] Geocontext, Geocontext, Center for geographic analysis, geocontext profiler, accessed: 2016-02-08 (2016).
URL http://www.geocontext.org/publ/2010/04/profiler/en/

[89] I. Muñoz, L. Milà-i Canals, A. R. Fernández-Alba, Life cycle assessment of water supply plans in mediterranean spain, Journal of Industrial Ecology 14 (6) (2010) 902–918.

[90] Deutsche Gesellschaft fur International Zusammenarbeit (GIZ), Guidelines for water loss reduction, a focus on pressure management, accessed: 2016-02-08 (2011).

URL https://www.giz.de/fachexpertise/downloads/giz2011-en-guideline-water-loss-reduction.pdf

[91] European Environment Agency (EEA), Assessment of cost recovery through water pricing, EEA, iSSN 1725-2237, Technical report No. 16/2013, Accessed: 2016-03-18 (2013).
URL http://www.eea.europa.eu/publications/assessment-of-full-cost-recovery

[92] R. Frauendorfer, R. Liemberger, The issues and challenges of reducing non-revenue water.

[93] Centro de Estudios y Experimentación de Obras Públicas (CEDEX), Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua, effecto del cambio climático en los recursos hídricos disponibles en los sistemas de explotación, centro de Estudios Hidrográficos, CEDEX: 43-308-5-001 (2012).

[94] Intergovernmental Panel on Climate Change, (IPCC), Emissions Scenarios, IPCC, accessed: 2016-03-18.
URL http://www.eea.europa.eu/data-and-maps/indicators/water-use-efficiency-in-cities-leakage/water-use-efficiency-in-cities-leakage

[95] Ministerio de medio ambiente, Gobierno de España, Precios y costes de los Servicios del Agua en España, EEA, directiva Marco Agua, Accessed: 2016-03-21 (2007).
URL http://www.chj.es/es-es/ciudadano/participacion_publica/Documents/Plan%20Hidrol%C3%B3gico%20de%20cuenca/Precios_y_costes_de_los_servicios_del_agua_en_Espa%C3%B1a.pdf

[96] European Environment Agency (EEA), Water use efficiency in cities, leakage, EEA, wQ06, Accessed: 2016-03-18 (2003).
URL http://www.eea.europa.eu/data-and-maps/indicators/water-use-efficiency-in-cities-leakage/water-use-efficiency-in-cities-leakage

[97] F. Liu, A. Ouedraogo, S. Manghee, A. Danilenko, A primer on energy efficiency for municipal water and wastewater utilities.

[98] Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de España, Planes hidrológicos de cuenca vigentes, web Page, Accessed: 2016-03-21.
URL http://www.magrama.gob.es/es/agua/temas/planificacion-hidrologica/planificacion-hidrologica/planes-cuenca/default.aspx

[99] Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de España, Anejo 9: Recuperación de costes de los servicios del agua en la demarcación hidrográfica del Tajo. Plan HidrolÃşgico de la parte espaÃśola de la Demarcación Hidrográfica del Tajo (2014).
URL http://www.chtajo.es/Informacion%20Ciudadano/PlanificacionHidrologica/Planif_2015-2021/Documents/PlanTajo/PHT2015-An09.pdf

[100] G. Wolff, R. Cohen, B. Nelson, Energy down the drain: the hidden costs of californiaâĂŹs water supply, Natural Resources Defense Council. New York, NY.

[101] L. E. Ormsbee, K. E. Lansey, Optimal control of water supply pumping systems, Journal of Water Resources Planning and Management.

[102] P. Jagals, L. Rietveld, Estimating costs of small scale water supply interventions, Valuing Water, Valuing Livelihoods: Guidance on Social Cost-benefit Analysis of Drinking-water Interventions, with Special Reference to Small Community Water Supplies,(Cameron J., Hunter P, Jagals P., Pond K., eds), IWA Publishing, London, UK (2011) 149–166.

[103] L. Hardy, A. Garrido, L. J. Sirgado, Análisis y evaluación de las relaciones entre el agua y la energía en España, Fundación Marcelino Botín Santander, Spain, 2010.