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Water Balance Calculations in Urban Area Catchments – Case Study Märstaån

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Local to Global Water Vulnerability and Resilience
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Abstract

This study has shown how to handle the impact of fresh water and waste water flows in water balance calculations for a semi-urban river catchment area. With help of a case study performed in Sweden a water balance formula has been evaluated then modified and used to identify important areas that affect water flows focusing on leakage of storm water into waste water systems.

Content

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1 Introduction

Water management has today become a local and global challenge while used to handle the existing water resources available as an ecosystem service. A long term water balance calculation is one way of presenting a quantification that will characterize the focused water resource issues.

The EU Water Framework directive (WFD) has been implemented in the Swedish law legislation to meet the requirements of good water status by 2015. Understanding the total water balance for a catchment area is an important part in this work. As shown by *Sokolov* and *Chapman* [1974] the inflow part in a catchment area comprises precipitation as snow/rainfall and surface/subsurface water for any rural natural water catchment. The outflow part includes evapotranspiration from the surface and subsurface water outflow.

Normally this is expressed as the following relationships for a full hydrological year when any storage can be excluded.

Input Precipitation (P) = Output Evapotranspiration (ET) + Output Stream flow (Q)

For urban areas storm water, once regarded only as a nuisance, is now increasingly regarded as a resource as shown by *Fletcher et al* [2012]. Urban hydrology will play a critical role in addressing this area. For urban and semi-urban areas the water balance calculation must also take into account the impact of sewage water. *Kenway et al* [2011] has shown that this approach makes visible large flows of water that have previously been unaccounted. The water balance calculations of an urban catchment were described by *Mitchell et al* [2003] as follow in equation 1.

$\Delta S = (P + I) - (E_a + R_s + R_w)$ (Equation 1)

ΔS is the change in catchment storage, including water held in the soil profile, groundwater aquifers, and natural and constructed surface water storages; P is precipitation; I is imported water; E_a is actual evapotranspiration; R_s is storm water runoff; and R_w is wastewater discharge. This equation is focused on the hydrological performance of a catchment and not an urban entity.

A similar equation was presented by *Bhaskar and Welty* [2012] when they stated "Urban water balances are generally unknown, yet they are necessary for assessing water availability in an urbanizing world and for understanding the effects of urbanization on the hydrologic cycle"

Despite the importance of urban areas, given half the world's population lives in cities, energy and water balance fluxes are rarely measured as shown by *Järvi et al* [2011]. Through evaporation the water balance is also linked to the energy balance which in urban areas has been shown by *Oke* [1987]

To investigate how to best calculate water balance in urban and semi-urban areas a case study has been done in a local catchment area, Märstaån, close to the Stockholm city in the central parts of Sweden. Here storm water, fresh water and waste water will be included into the water balance calculation.

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2 Material and Methods

2.1 Case study - Märstaån catchment

The Märstaån catchment is situated just north of Stockholm, Sweden and the area is approximately 80 km^2. It belongs to the Northern Baltic Sea River Basin District and drains via the lake Mälaren and the Norrström catchment to the Baltic Sea. In Figure 1 the Märstaån catchment is outlined together with other catchment areas with green lines and major streams (-ån). Within the catchment area there are approximately 25000 inhabitants most of them living in the Märsta city area.

Figure 1 Situation of the Märstaån catchment in the lake Mälaren (Norrström) catchment area. (Wallin 2000)

The Märstaån water is not used as a resource for irrigation or fresh water supply as the quality is affected by nutrients and toxic substances as that will be discussed in chapter 2.1. Processed waste water from Arlanda deicing activities and condensation water from heat production is fed into the river for transport to the lake Mälaren [*Norling* 2011].

2.1.1 Climate

The temperature yearly mean value for Sweden for the years 1961-1990 together with monthly mean values from the SMHI station at Arlanda airport is presented in Figure 2. The catchment area, marked with a star, is situated in an area that has a long term average temperature of 5-6 °C.

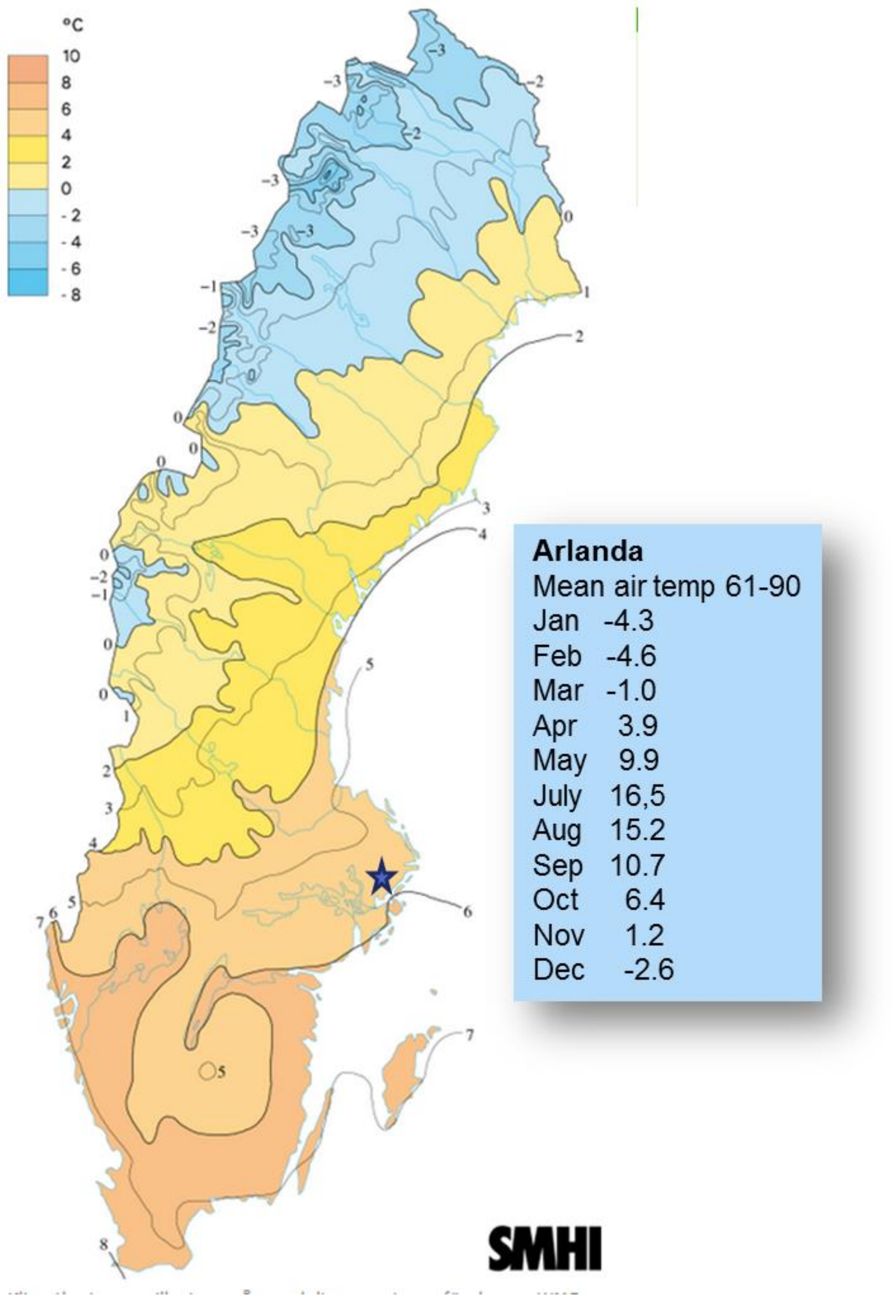

Figure 2 Sweden mean temperatur 1961 -1990 and monthly means from Arlanda airport within the catchment area marked with a star. (SMHI)

2.1.2 Land use

Land use is semi-urban with a lot of industrial areas and the international airport of Arlanda. Still there is significant woodland and agricultural areas left, see Figure 3 and Table 1 Land use [*Pansa*r 2013].

Land use	**Area ha**	**%**
Farm land	2189	28
Cattle	383	5
Woodland	2999	39

Urban parks	185	2
Water	50	1
Other	76	1
Industrial	321	4
Arlanda	1023	13
Urban area	497	6
Totalsumma	7725	100

Table 1 Land use

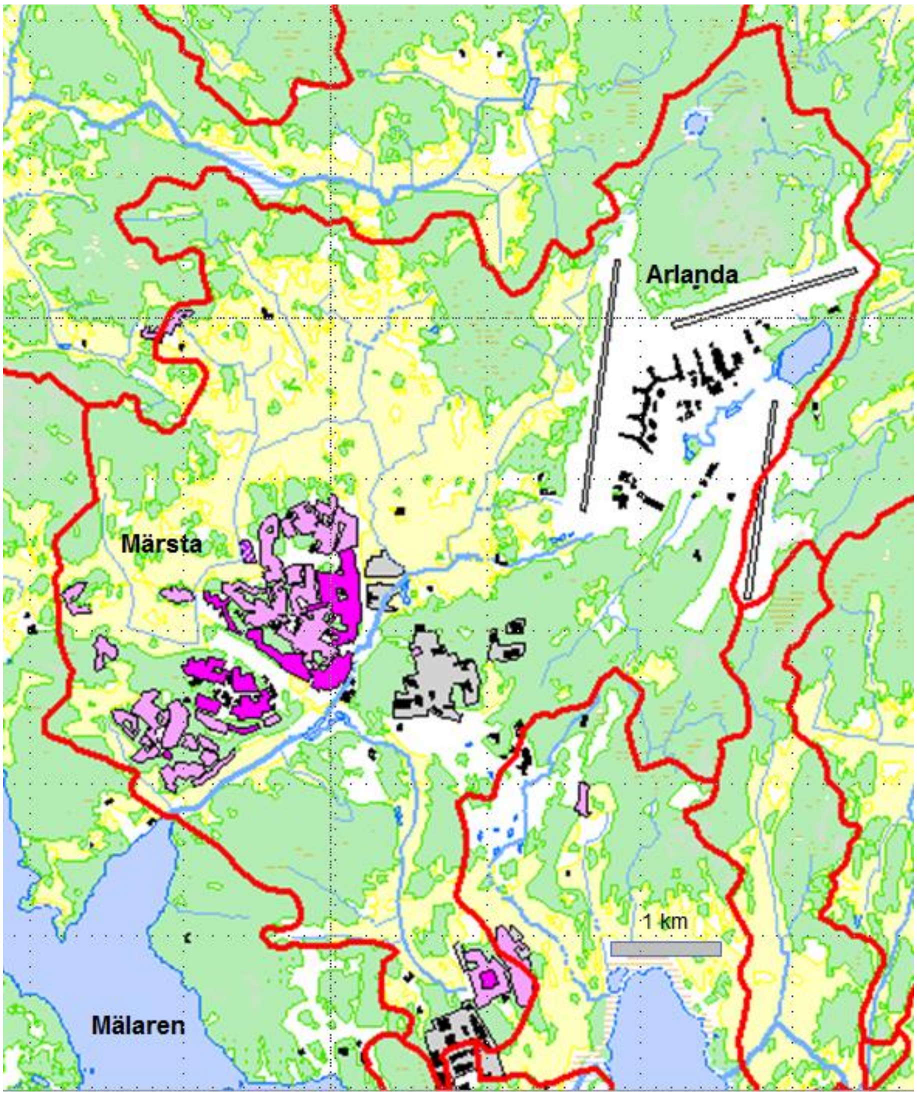

Figure 3 Catchment Märstaån outlined in red. Agriculture areas are marked in yellow and urban areas in brown. Catchment Märstaån outlined in red. ©Lantmäteriet Gävle

2.1.3 Topography

The topography is dominated by river valleys and some small hills in the Märsta area and north of the Arlanda airport. In Figure 4 low lying land is presented in bluish color starting from 1m above sea level, mostly consisting of agriculture areas. Hills are presented in red colors reaching up to 65m above sea level.

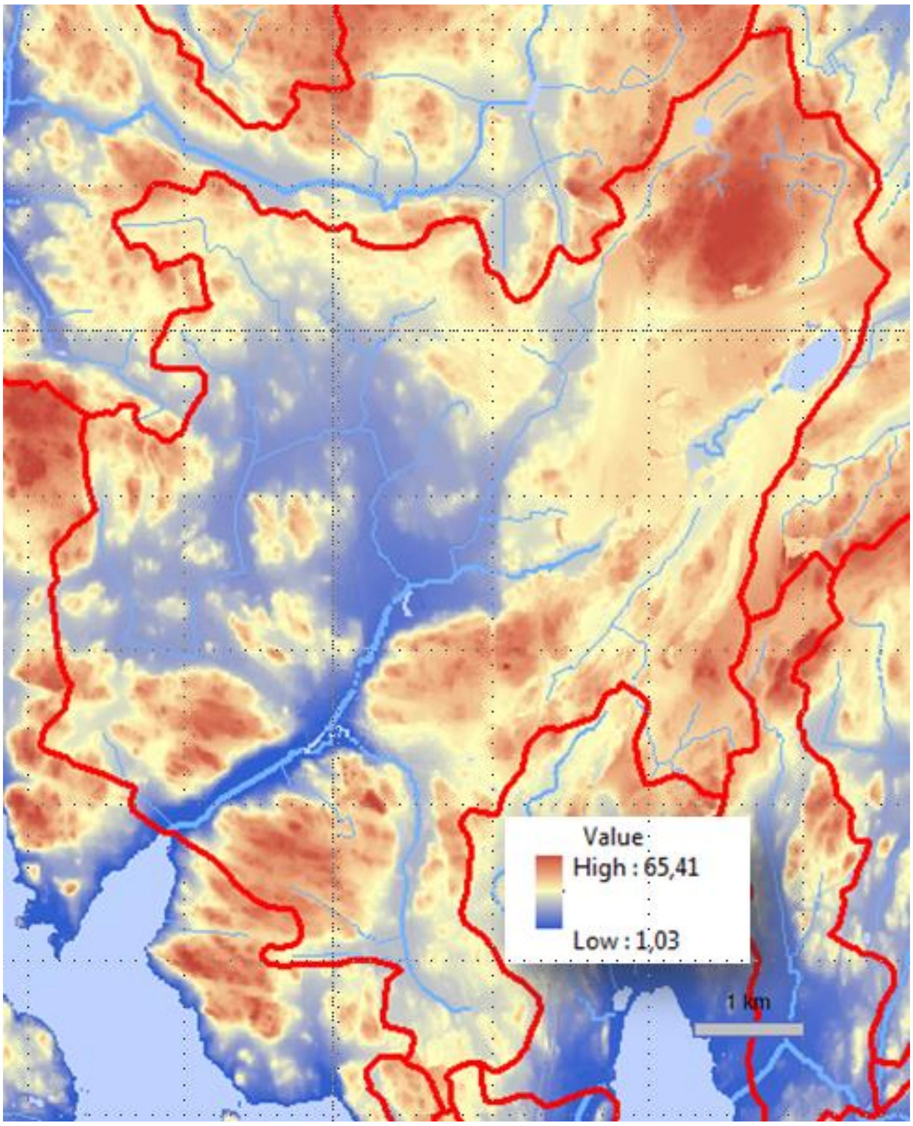

Figure 4 Catchment Topography shown with 2m resolution radar data. Catchment Märstaån outlined in red. (SLU 2013).

2.1.4 River system

From northeast the small tributary Halmsjöbäcken stream connects at the reference point F after running through/under the Arlanda International airport. The actual part that is named Märstaån starts at reference point F and run mostly underground in the" Moralund tunnel", see Figure 5. The reference point F is where the airport impact on the Märstaån water quality is measured. The operations of Fortum Heat and SÅAB Recycling are situated in the Brista valley south of point F as described by *Norling*[2011].

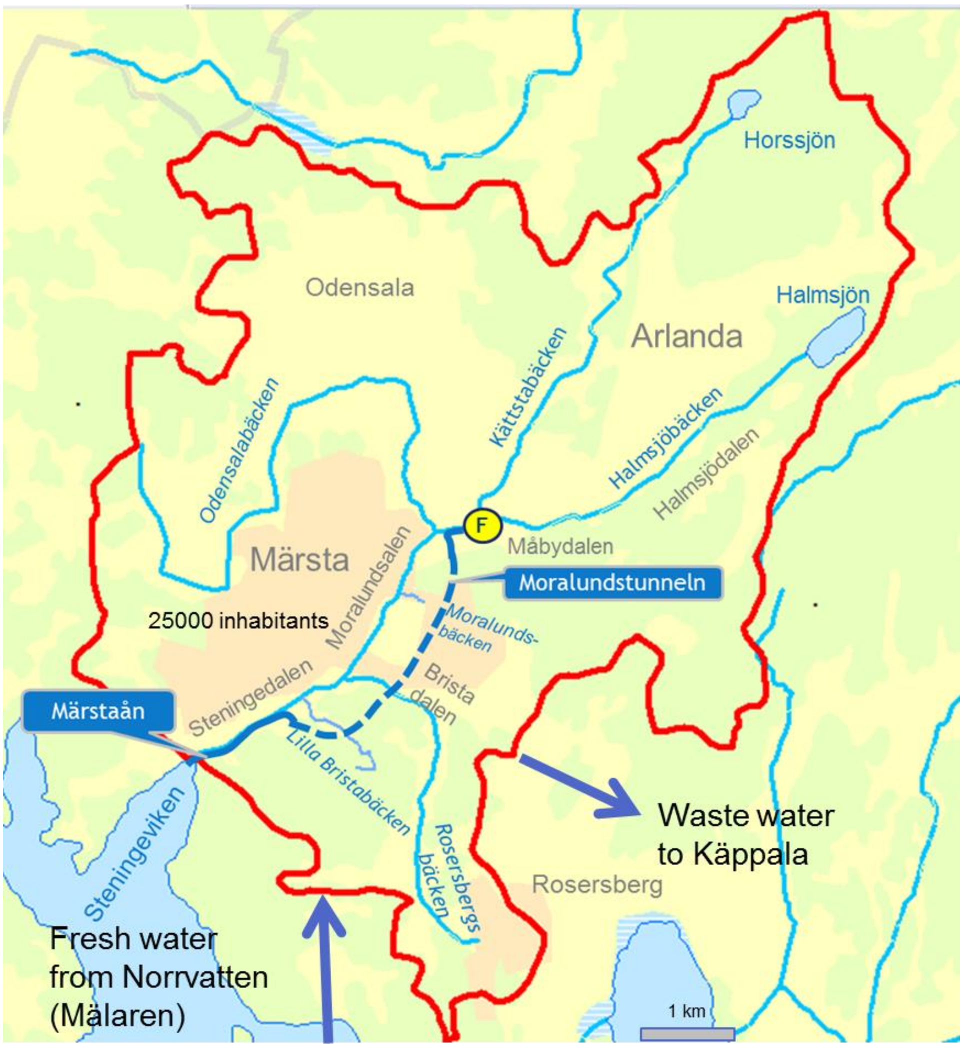

Figure 5 Märstaån river system with the reference point "F" marked with a yellow circle. Catchment Märstaån outlined in red

2.1.5 Fresh water - Storm water - Waste water systems

Fresh water comes from the lake Mälaren and the intake is just downstream of the Märsta river outlet. Waste water is feed through a tunnel to the Käppala Waste Water plant east of Stockholm in the Baltic sea archipelago, see Figure 5.

Storm water from the catchment area is fed to a nearby stream or to a storm water dam for local treatment and habitat protection in order to maintain biodiversity. An overview of the flows is presented in appendix 1. Guidelines on how to take care of storm water is detailed in [Oxunda vattensamverkan 2007].

Waste water and leakage water consists of three different flows as can be seen in Figure 6:

1. Ground water that leaks drains to the sewage water pipe
2. Rain water that flows directly into the waste water pipe
3. Indirect rain water flow making ground water flow into the waste water pipe or leakage between storm water pipes and waste water pipes

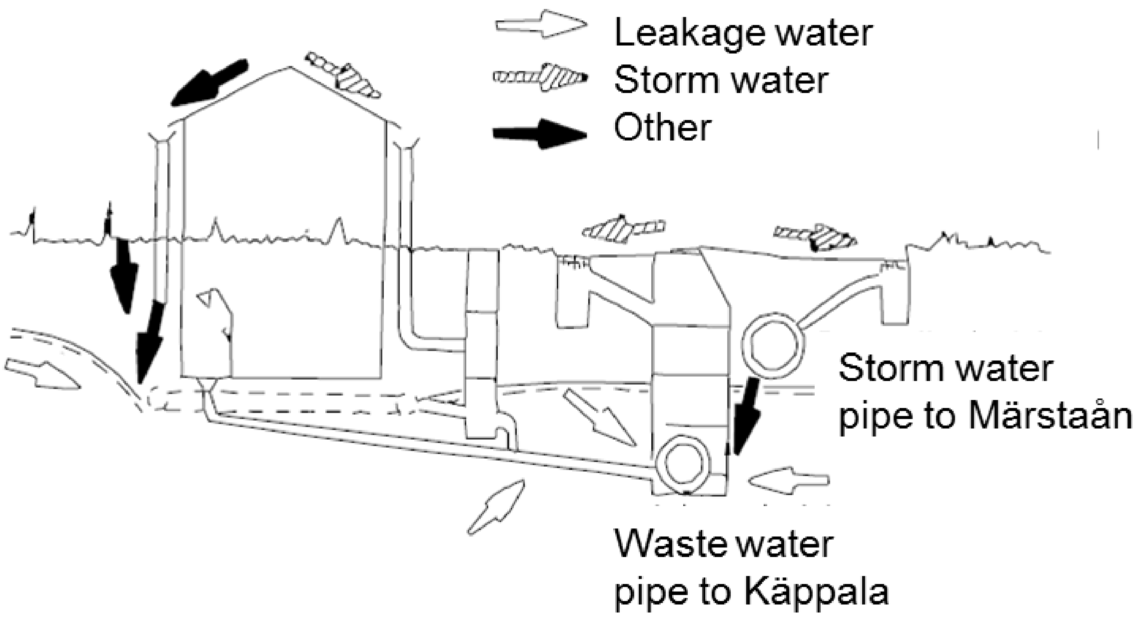

Figure 6 Waste and stormwater flows [*Adrup* 2013].

The origin of the water flow in the Sigtuna County waste water pipe to Käppala for the year 2010 to 2012 is shown in Figure 7 [*Adrup* 2013].

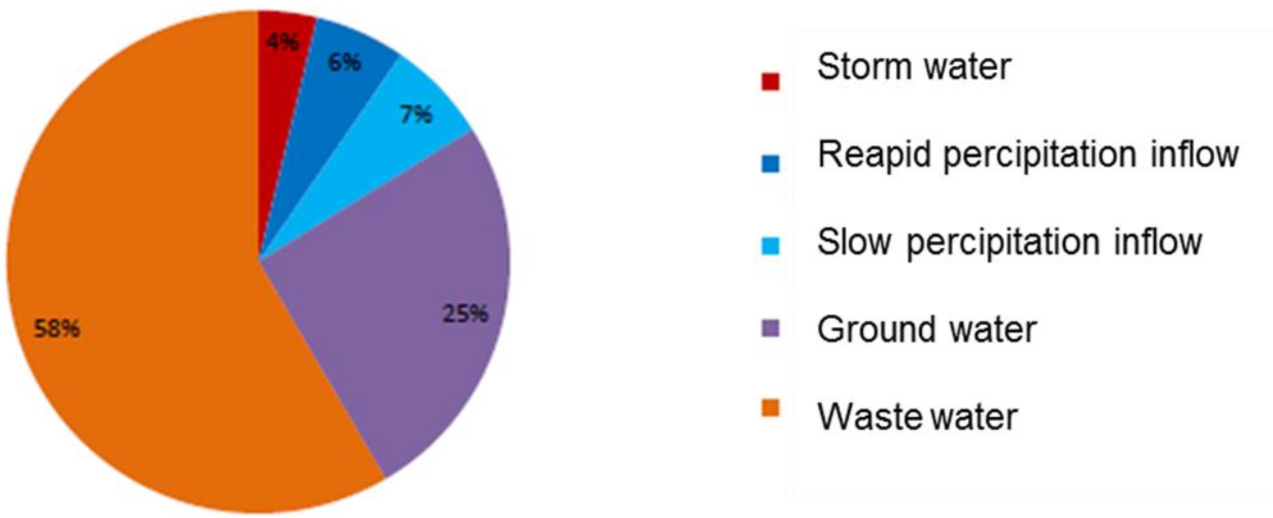

Figure 7 Waste water origin 2010 – 2012

2.1.6 Märstaån Catchment Water Management

To handle the local water management the Märstaån Water Council was formed in January 2011. The activities are driven by the County of Sigtuna where the catchment is located. Members are all the major actors/operations in the catchment area and also a representative from the Stockholm County Administrative Board that has the responsibility to ensure that the EU Water Framework Directive is implemented correctly. The Stockholm County Administrative Board also collects some of the water quality and presents them in a yearly report, Märstaåns vattenkvalitet, financed by the water council [*Pansar* 2013].

The Märstaån "Water council vision and goals" document state that the council should be perceived as a good example for other councils in Sweden and that their common water will make them proud and expectant for the future. In their goals they also state that knowledge about ecological and chemical quality is important and they are building a common recipient reporting system covering most of the area. More specific they state that the status in all parts shall be regarded as good/green at the latest in the year 2021, instead of 2015 [*Norling* 2013].

The VISS (Water Information System Sweden) database states the overall water quality requirements from the EU level and contains maps of all major lakes and watercourses in Sweden and for all these waters catchments there is information regarding the status classification and the assessment of water quality. The ecological and chemical status for Märstaån is shown together with an assessment of the risk that it will not meet the goals set for the year of 2015. Today the risk is marked as "red" on the ecological status due to problems from eutrophication and environmental toxins. An example of available information is presented in Figure 8.

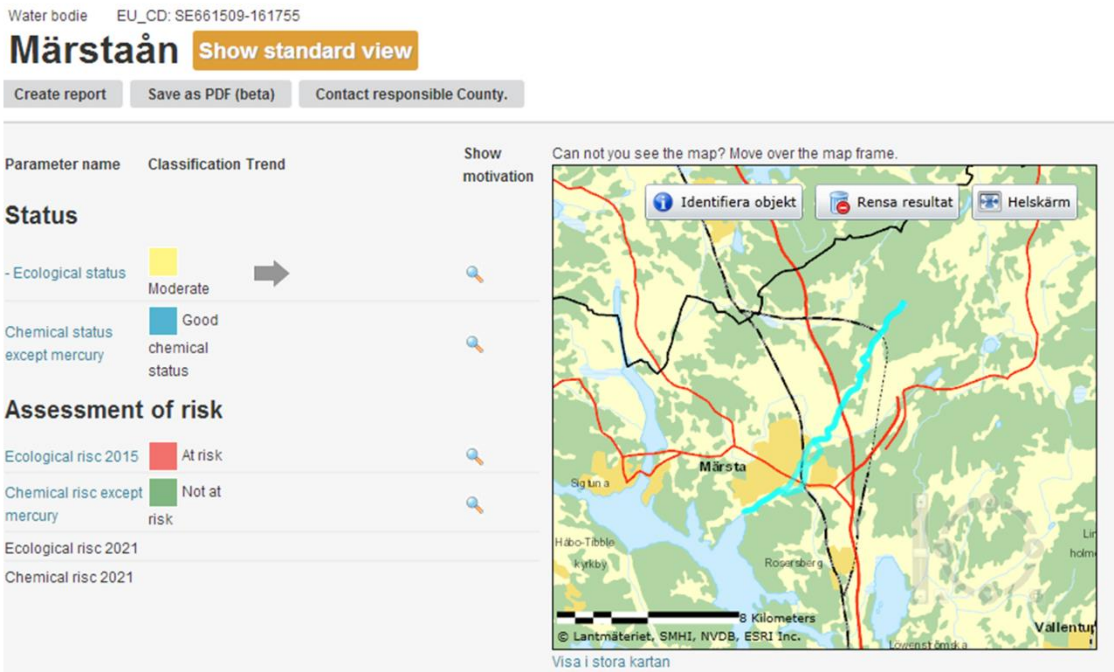

Figure 8 VISS Water quality overview for the Märstaån catchment

(http://www.viss.lansstyrelsen.se/Waters.aspx?waterEUID=SE661509-161755&userProfileID=3)

Water management focuses areas of today listed by *Norling* [2013] are:

- Cadmium pollution from airport facilities
- Leakage of fluorinated surfactants (PFOS) from the old firefighting exercise grounds at Arlanda
- Cadmium content in heat production condensation water at Brista will no longer be permitted by Käppalaverket.
- Condensation excess water cannot be fed to the Märstaån River when the river flow is below a certain volume. This is likely to happen in winter time when Fortum needs the full capacity of the heating plants.
- Flooding of the dam system at heavy rain storms on the recycling and deposit operations in the Brista valley.
- Reduction of Nitrogen and Phosphor leakage from farm lands.
- Nitrogen, Phosphor and organic material originating from runway and aircraft deicing in winter time.
- Invasive species like the marbled crayfish.

There is a trans boundary issue in the catchment area as Swedavia is overall responsible for the water management and quality upstream of their advanced monitoring station at reference point "F", see Figure 9 .

Figure 9 Swedavia measurements in reference point "F" measuring important water quality parameters and water flow [*Norling* 2011]

This is part of the continuous water monitoring covering Arlanda International Airport but also some agricultural land not belonging to Swedavia but affecting nutrients levels. This monitoring is complemented with sample monitoring from other parts of the catchment.

2.2 Input Data for Water Balance Calculations

2.3.1 SMHI Models

To get an overview of expected long term average values for the evapotranspiration from 1961 – 1990 years data from SMHI was used and presented in Figure 10.

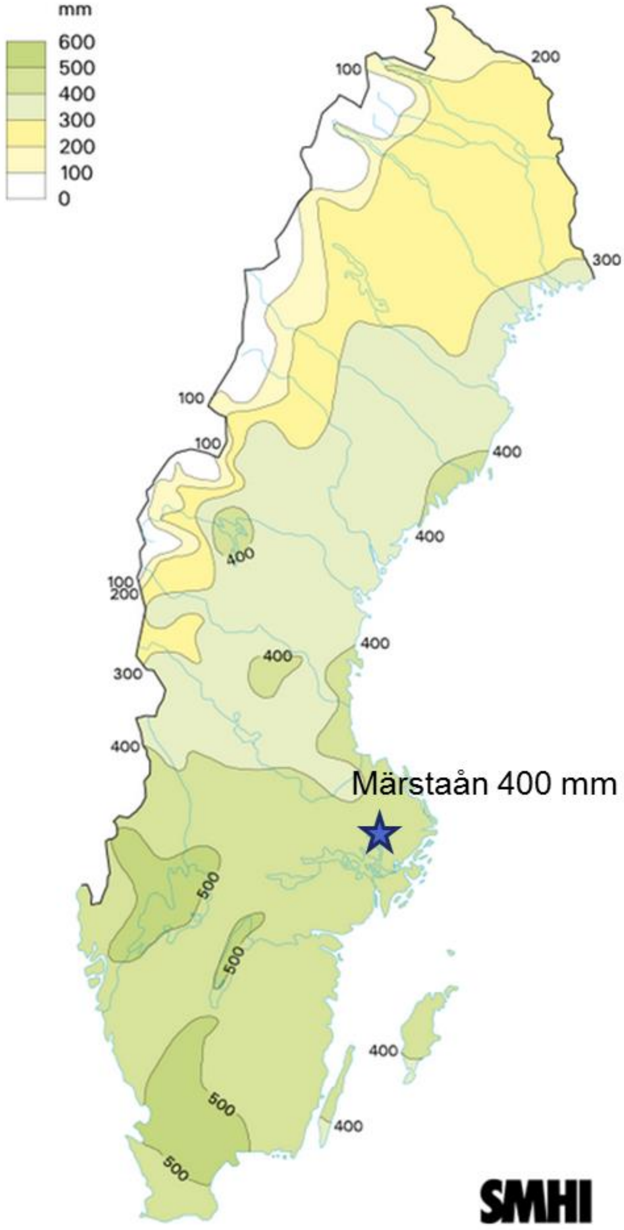

Figure 10 Evapotranspiration data from Sweden. Average yearly values for 1961-1990. Value for the position of the Märstaån catchment around 400 mm/year.(SMHI)

2.3.2 Precipitation data

There is long term information about precipitation available from the town of Uppsala just north of the Märstaån catchment. The data is presented together with information about extreme values and for wet and dry years in Figure 11.

Arrival Time	Precipitation	
	Wet	Dry
Extremaste 1835-2010	812	301
1:100	771	341
1:50	743	364
1:20	703	399
1:10	667	430
1:5	625	469
Average 1835-2010	549	

Figure 11 Mean yearly precipitation data from Uppsala just outside of the catchment area. Arlanda MKB (*Swedavia* 2011) .

2.3.3 Stream flow

The output stream flow is measured at regular time intervals at the point where Märstaån is flowing into the lake of Mälaren, see Figure 12 made by *Pansar* [2013].

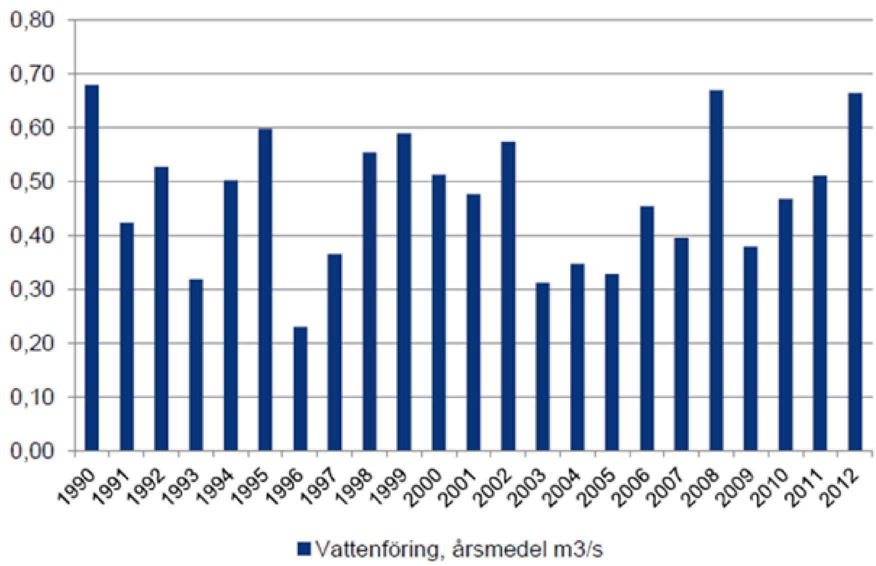

Figure 12 Modeled average yearly flow values in the Märstaån river (SMHI)

2.3.4 Waste and leakage water

Sewage water sent to Käppala can be divided like what can be seen in Figure 13 [*Adrup* 2013]. Leakage water is presented as red color. The current county development plans within the Käppalaverkets service area [RUFS 2010] indicate that even more leakage water will come into the system bringing it to its max capacity soon [*Adrup* 2013].

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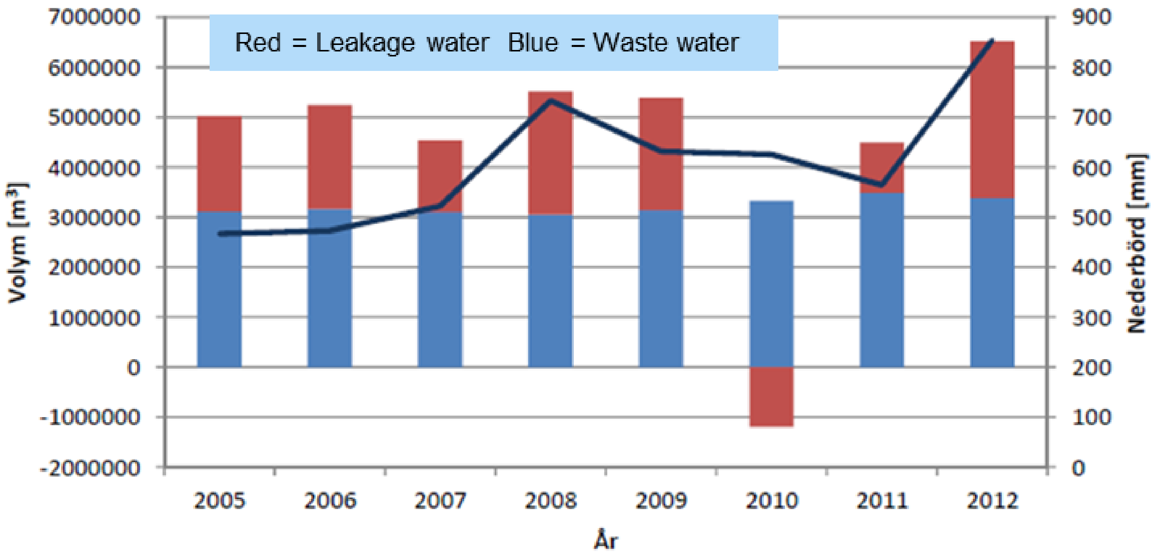

Figure 13 Waste water and leakage water flow to Käppala from Sigtuna county. Values for 2010 affected by faulty measuring equipment

2.3.4 Fresh Water

Fresh water consumption for Sigtuna County for the year 2005 to 2012 is presented in Figure 14 [*Adrup* 2013].

Område	Anslutna spillvatten-ledningar, m	Försåld dricksvattenvolym [m³]							
		2005	2006	2007	2008	2009	2010	2011	2012
MR01 - Löwenströmska	153 000	3 113 712	3 161 912	3 104 284	3 056 152	3 140 123	3 332 500	3 486 379	3 386 563

Figure 14 Fresh water consumption for the Sigtuna County in m³

2.4 Study objectives and the study approach

The following questions will be the focus for the analysis on how to calculate water balance in a semi-urban area.

- What is the correct evapotranspiration formula to use for the case study area
- How will the evapotranspiration values change when storm water and sewage water are included in the calculations

Based on earlier research, described in chapter, 1 the formula presented by *Mitchell et al* [2003] and, shown as equation 1, seems appropriate to use in the Märstaån catchment where fresh water is coming in and sewage water is going out from the catchment area.

For the case study water balance calculations the adapted formula to use will be;

P (precipitation) +F (freshwater) = E (evapotranspiration)+Q (storm water) + W(waste water) + E (Leakage water)

E = P+ F - Q - W - L (Eq 2)

The change in catchment storage, groundwater aquifers, and natural and constructed surface water storages is not included as the calculations run over complete hydrological years.

Figures covering all of Sigtuna County are adjusted to 50% to represent the Märstaån catchment. Calculation is done with and without taking waste and fresh water figures into account showing how a semi-urban area impacts the water balance calculations. Normally waste water delivery should equal fresh water consumption for the catchment area [*Adrup* 2013] and not affect the evapotranspiration figures.

The flow in the Märstaån River, Q, is measured at the output in the Steningeviken, a part of Mälaren, see Figure 12. Most other calculation done so far are (Stockholm County, Swedavia, SMHI) are using the average figure **Q** =0.5 m^3/s. = 15.552.000 m3/year = 200 mm/year

The precipitation values are presented in Figure 10. The average figure from year 1835 -2010 will be used. **P** = 549 mm/year

Fresh water consumption **F** as presented in Figure 14 will use the 50% average value of 1 650 000 m3/år = 0,02 m3/m2/y= 21 mm/y

Waste and leakage water figures presented in Figure 13 are affected by malfunction in the measuring equipment so adapted average figures will be used in the calculations.

Waste water (Sewage) will use the 50% average value of 1 500 000m3 / y =0,02 m3/m2 /y = 19 mm/y

Leakage water **L** is storm and ground water flowing into the Käppala tunnel system and will use the 50% average value of 1151000 m3/y = 0.014 m3/m2/y = 15mm/y

3 Results

Using the adapted formula (Eq 2) and the input data presented in chapter 2.4 the yearly average evapotranspiration value can be calculated. As storage volumes are not part of the calculations only yearly average values will be used. All values will be presented as mm/year using the catchment area 7728 ha = 77,28 km2 = 77.280.000 m2.

Result without waste/freshwater:
Evapotranspiration = 549 (rain) – 200 (runoff Märstaån) = 349 mm/year

Result with waste/freshwater included:
Evapotranspiration = 549 (rain) + 21 (fresh water) – 200 (runoff Märstaån) – 19 (waste water to Käppala) – 15 (leakage) = 336 mm/year

See overview in Figure 15.

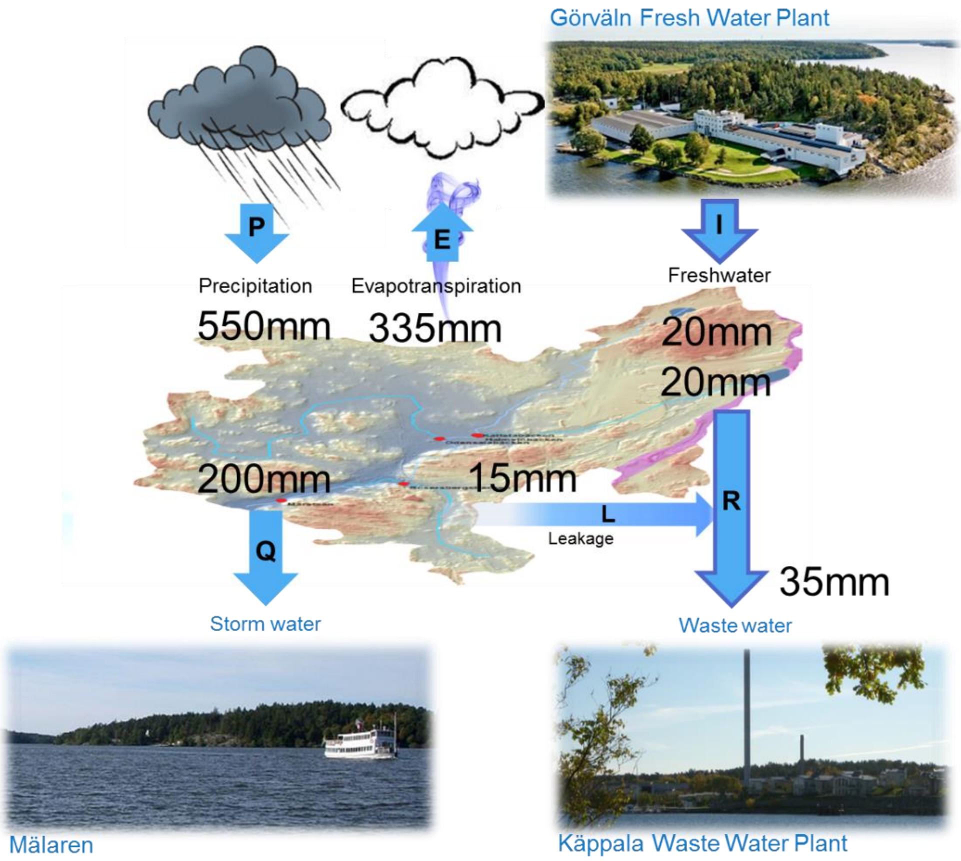

Figure 15 Märstaån water balance model Evapotranspiration = 550 (rain) + 20 (fresh water) – 200 (runoff Märstaån) – 20 (waste water to Käppala) – 15 (leakage) = 335 mm/year

As a reference the Arlanda Fresh Water consumption is 530 000 m3/year = 6,85 mm/y and Arlanda sewage output equals 560 000 m^3/y = 0,72 $m^3/m^2/y$ =.7,2 mm/y

4 Discussion

The use of runoff/storm water in the area is minimal as no major irrigation or other use is present. Low flows in the Märstaån River during the winter period can even tough result in toxic concentrations with levels above what is acceptable. This is difficult to address with a water balance calculation that works with hydrological years. A water model with monthly values could be developed showing all the catchment s water flows going in and out and used when prioritizing what areas to address in short and long term perspective.

The Märstaån catchment areas major water balance related flow problem is the high amount of runoff/storm water and the leakage into the Käppala waste water system. This can be addressed with the equation presented in this paper (Eq2)

The precipitation value using the formula E=P-Q gives a value of about 350 mm/year. Adding the influence of fresh, waste and leakage water, E=P+F-Q-W-L, the precipitation value drops to 336 mm/year almost down 5% when using the adapted formula described by Mitchell et al [2003].

The difference shown in the overview Figure 15 relates to the leakage from storm and ground water into the waste water tunnel. As snow smelt and at heavy rainfall the waste water flow to Käppala raises significantly as leakage water from storm water systems comes into the waste (sewage) system. As the Märstaån catchment area is located in a rapidly growing county, now building the Arlanda Town complex, the storm water related problems related to high flows (and to some extent ground water) will grow in the future. Large logistic centers under construction mean many large buildings and lots of hard surfaces. Together with the expected total rise in waste water flow within the Käppala waste water plant service area this will likely become a major problem for the Stockholm region.

Using this kind of water balance calculations shown in this report (Eq2) will highlight the importance of improving evapotranspiration in the catchment as a mean to reduce the flow to Käppala.. This means that storm water and impact of slow and rapid rainfall has to be kept at a minimum in order to reduce leakage into the Käppala tunnel.

This implies an even bigger effort of taking local care of storm water and rainfall by having more green areas, green roofs and dams. This will also positively affect the water quality problems in the Märstaån River [*Oxunda vattensamverkan* 2007].

It would be of interest to investigate if it is possible to calculate accurate transpiration figures from the different kind of surfaces that exists within the catchment area. One method could be to use interpretation and categorization of vegetation and landscape from Color IR stereo aerial photographs and an analysis with GIS.

If transpiration data can be found for different kinds of meadows, deciduous and conifer woodlands including coverage percentages and tree height information this could be used to build a biotope map with a layer for calculated transpiration. An analysis could then propose how to change land use in order to maximize evapotranspiration and reduce storm water inflow to the waste water system.

5 Conclusion

For an urban/semi-urban catchment storm and sewage water should be included in any water balance calculation as they affect the result. Especially this is important if there is a leakage of storm water into waste water pipes.

The result from these water balance calculations for the case study Märstaån highlighted that higher evapotranspiration figures will minimize waste and storm water flows.

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Appendix 1 Storm water flow and treatment for the Märstaån catchment