Study of the impacts of climate change on the performances of constructed wetlands managing and treating stormwater in urban areas.

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Executive Summary

In a time of continuous urbanization, increased stormwater runoff due to expanding impervious surfaces causes downstream erosion and floods and lowers water quality. Constructed wetlands have been developed in the last few decades as environment-friendly and cost-effective alternatives to traditional stormwater management systems. They retain water and help it infiltrate the soil which makes them a useful tool for stormwater management in urban areas. They also act as natural filters and are able to process polluted water to a certain extent.

France has been among the first countries to get interested in constructed wetlands and uses many of them to regulate the flow of rivers like the Seine. The country is also building more and more wetlands for stormwater management and water treatment.

The design and efficiency of constructed wetlands depends on local climate (temperature, precipitation). With climate change, it is important to consider how constructed wetlands and their performances could be impacted by future climates. Surprisingly, this field has not been studied much yet.

This paper identifies the main characteristics of climate change in France according to the area. Then, the impacts of these climatic changes are studied on three different case studies. Solutions to mitigate the impacts of climate change are then proposed.

Constructed wetlands today

A literature review highlighted the current treatment performances of constructed wetlands. They can generally treat sediments and organics very well but can have issues with nutrients like nitrogen and phosphorus or pollutants very hard to decompose like de-icing salts (see Table).

	Overall performance
Sediments (TSS)	Good
Carbon (COD or BOD)	Very Good
Nutrient (Total Nitrogen)	Moderate
Nutrient (Total Phosphorus)	Not Good
De-icing salts	Not Good
Bacteria	Good

Climate change and its impacts

The main changes in climate that could impact constructed wetlands in France are summed up along with their associated impacts determined through three case studies. The case studies were located in areas with different climates: Marcy l'Étoile in the warm southern Mediterranean climate, Challex in the Alps mountains and Orly Airport in the very urbanized area near Paris with a colder moderate climate.

- **Temperature increase**: average temperatures have already started to rise and this could affect the biologically-controlled reactions of the wetlands.
  Impacts: potential boost of nitrification and other microbiological reactions especially in winter, reduction of source pollution (like de-icing salts) in the cold season.
- **More frequent and intense droughts and heatwaves**: can affect the health of the whole ecosystem of the wetland for which a prolonged lack of available water could be dramatic.
  Impacts: Lack of water and soil moisture could decrease or kill the vegetation of the wetland thus decreasing its overall treatment abilities. Surface flow wetlands which always need water-saturated conditions could be the most impacted.
- **Floods and increased runoff:** in mountains with melting glaciers and early melting of the snow, floods could increase. In urban areas in general, impervious surfaces lead to higher stormwater runoff volumes and even floods from intense rain events.
  Impacts: Constructed wetlands are designed to receive a maximum amount of water and could be unable to deal with this. Subsurface flow wetlands would be more impacted because they need enough time without water on their surface to regenerate the oxygen necessary to the reactions happening in the wetland.

Furthermore, it is important to consider that the total impact of climate change will result from **cumulative effects** which is different from just the sum of the separate impacts we identified.

Mitigating the impacts

Solutions are needed to mitigate those impacts and maintain the performances of constructed wetlands despite climate change.

In **warm climates**, resilience to droughts should be increased by adapting the design of the constructed wetland (subsurface flow, smaller surface) and using drought-resistant plants. Fresh- or grey water could also be fed to the wetland during the dry season to maintain the vegetation.

In **flood-prone areas** where increased runoff and floods are the main issue, the wetland design could also be adapted: surface flow, larger sedimentation pond, multiplication of the parallel filter beds. A water tank could also temporarily store the surplus of water during floods thus protecting the wetland.

For **very polluted water** like at Orly Airport, phytoremediation can help improve remediation performances. If this is not sufficient, it is also possible to add a supplementary treatment stage after the wetland or dilute the still-polluted water with clean water.

To conclude, climate change will have an impact on the performances of constructed wetlands in urban areas. More research is needed on cumulative impacts of future climates on wetlands and what mitigation strategies are best to counter them.

Introduction:

During the 20th and early 21st century, urbanization has not stopped increasing and approximately two thirds of the global population is expected to live in a city by 2050 (WHO 2014). Both densification of pre-existing urban areas and spreading of their outskirts have resulted in widespread land-use change (Gerten et al 2019). One of the drastic changes that comes hand in hand with urbanization is the increase of impervious surfaces.

Impervious surfaces prevent any infiltration of the water into the soil so stormwater will produce runoff in high volumes and with a high velocity that can cause erosion in receiving waterways (Chester and Gibbons 2007). Furthermore, as rainwater washes the roofs, roads and parking lots, it brings with it hydrocarbons, heavy metals and other pollutants which makes runoff an important transportation vector for pollution (Chester and Gibbons 2007). Because of this, people have created stormwater treatment systems that remediate pollution to a certain extent before stormwater is released into the receiving water body. However, traditional systems can be overloaded by an intense storm event leading to the release of untreated water (Scholz 2006 Chapter 3).

With 80% of its population living in cities (Statista 2021) and impervious surfaces doubling in 30 years to reach more than 6% of all its soils in 2011 (Comité pour l'économie verte 2014), France is not foreign to these issues. For example, the Seine River downstream from the area of the Greater Paris - the most densely populated area in France - has frequently low oxygen conditions caused by organic pollution from stormwater runoff (in summer low flow periods) (Boët et al 1999).

In the last decades, new approaches have been developed to deal with stormwater and water treatment in urban areas. Constructed wetlands are seen as an environmental-friendly and cost-effective alternative to traditional systems. They can replace drainage systems by retaining stormwater and helping it infiltrate the soils. This decreases runoff from impervious surfaces and its damage (downstream erosion, floods). Constructed wetland have economic advantages when used for water treatment because they act as natural and passive filters that do not require energy inputs (Scholz 2006 Chapter 16). Thanks to their passive nature, operation and maintenance costs are cheaper than traditional water treatment plants (CH2MHill 2014). Finally, they present social and environmental advantages like offering a natural habitat for wildlife in an urban setting and increasing life quality for city dwellers by reducing heat island effect and providing a recreational area (US EPA 1995a, CH2MHill 2014).

Different designs of constructed wetlands exist to adapt to different purposes and constraints. For all the designs sizing is done based on local climatic data like the intensity and frequency of precipitation, average temperatures, etc. (CH2MHill 2014). This can become an issue over the long lifespan of wetlands - that are built to last at least 20 years (CH2MHill 2014) - because those data can change. Climate change especially, is expected to bring increased temperatures and affect water level and availability (NOIGW 2009). The performances of constructed wetlands could thus be impacted and they could not work properly anymore. The resilience of wetlands to climatic changes is thus very important but has not yet been studied a lot. More research is necessary to determine what measures are needed to improve the resilience of already established systems and adapt the design of new ones.

Objectives and Methods

The objectives of this paper are to identify the climatic events that climate change will probably bring in the near future in France and then to identify the impacts of those events on constructed wetlands that were built for stormwater management and treatment in urban areas.

To do that, a literature review will be conducted, first on constructed wetlands and then on climate change in France. Finally, we will use three case studies of constructed wetlands to analyze through concrete examples the impacts that climate change can have on wetlands that deal with stormwater in urban areas. The case studies are located in different areas of France to get a full picture of the different climates that exist in mainland France. The first one is located on the southern half of France characterized by a warm climate, the second in the Alps and has a climate typical of mountainous areas and the last is near Paris with a temperate climate more typical of the northern half of France.

I. State of the art: Constructed Wetlands in France

A. What are constructed wetlands and what can they do

<u>Constructed Wetlands</u>

Urban areas face the challenge of dealing with high volumes of polluted runoff and treating all the water released in the sewers by households - called domestic wastewater - while having very little space. The usual solution is to build a treatment plant outside of the city. Urban stormwater traditionally goes through drainage systems that work on an "end-of-pipe" principle which means that stormwater is evacuated as quickly as possible and then treated in the plant. The issue this method encounters is that extreme storm events or an increased runoff volume caused by the impervious surfaces covering urban areas can overload the drainage system. The treatment step is then bypassed, and polluted or only partially treated water is released in receiving waters (Scholz 2006 Chapter 16).

Constructed wetlands are a natural alternative to these systems that present many advantages. To understand that, let us first define what they are:

Wetlands are difficult to define, as various areas and ecosystems fit the term. The key element that characterizes a wetland is the presence of water-saturated ("wet") conditions (Scholz 2006 Chapter 16). The wetland can be always "wet" or only for short periods of time. Because of this unstable state between terrestrial and aquatic conditions, wetland biodiversity is adapted to water-saturated conditions and sudden changes.

Constructed wetlands, unlike natural ones are artificially created. They are often designed for one main purpose which will influence their design and appearance. These purposes are explained below.

Biodiversity & Recreation

A first purpose is biodiversity conservation. Natural wetlands are known to harbour a large variety of organisms (US EPA 1995a) but they are getting destroyed to be replaced by urban or agricultural lands. So, some constructed wetlands aim at protecting biodiversity by becoming a substitute for these lost natural habitats. In urban areas, constructed wetlands also offer the advantage of creating a green space where recreational and/or educational activities can take place. They increase life quality and can even raise the surrounding property value (US EPA 1995b).

Flow control

Constructed wetlands can also be built to regulate stream flows and prevent floods. For example, a series of retention ponds and weirs have been built upstream of Paris to maintain the Seine level in a certain range in the city (Boët et al 1999). This system of wetlands serves alternately to store water to prevent floods and to release water to maintain a navigable level.

Stormwater management & water treatment

What interest us most in this paper is that wetlands can help for stormwater management and water treatment and replace traditional “end-of-pipe” systems for a lesser cost as the system is passive (it does not require an energy input to function) (CH2MHill 2014). Stormwater that reaches the wetland will settle there for several hours to several days which is called the retention time, before being slowly released downstream. This retention time also allows some water to infiltrate the soil and the wetland to work as a natural filter (Scholz 2006 Chapter 16). In France, constructed wetlands have been used for decades to treat domestic wastewater. More than 3500 constructed wetlands are currently used by small rural communities as only treatment for domestic wastewater with concluding results (Morvannou et al 2015).

Both stormwater management and domestic wastewater treatment are often combined because most of the urban areas in France have a system called “combined sewers”. This means that the pipes evacuating stormwater are the same as the sewer pipes where domestic wastewater flows. So both type of water are mixed during storm events and they end up in the same place (treatment plant or constructed wetland). This makes the volume of water - called hydraulic load - very variable as well as pollution levels. Constructed wetlands thus need to be able to adapt to those variations in order to function well.

B. Designs of constructed wetlands

Constructed wetlands can have various designs depending on the aims, the amount of runoff variability and the contaminant types and loads.

Surface flow

Surface flow wetlands are shallow basins (less than 45cm deep on average) containing water above the surface of the soil and a dense vegetation of rooted emergent plants (CH2MHill 2014). Water enters the basin and flows very slowly towards its outlet. During the period when water is retained, its low velocity allows sediments to settle and most pollutant to be sorbed (taken) by the bottom soil or decomposed by the organisms living in the wetland (USEPA 1995a).

Surface flow wetlands are the closest to natural wetlands like marshes, and as such, they are the best option as a wildlife habitat and for biodiversity conservation. Their appealing aesthetic appearance also makes them appropriate as recreational areas. They can also be used for stormwater detention and treatment as well as agricultural runoff treatment (USEPA 1995a). However, the ability to improve water quality depends directly on the time water spends in the wetland. Water has to travel a long way in order to stay longer (CH2MHill 2014) so this kind of wetland takes up a lot of space.

Subsurface Horizontal Flow

Subsurface flow wetlands are basins with water below the surface of the soil. There are two types of subsurface flow wetlands according to the direction of the flow.

Horizontal flow wetlands are made so that water flows horizontally in a porous media that also contains the roots of the vegetation planted on the wetland (Figure 1). They are not very deep but like the surface flow wetlands, they can require a large area to make water travel enough distance.

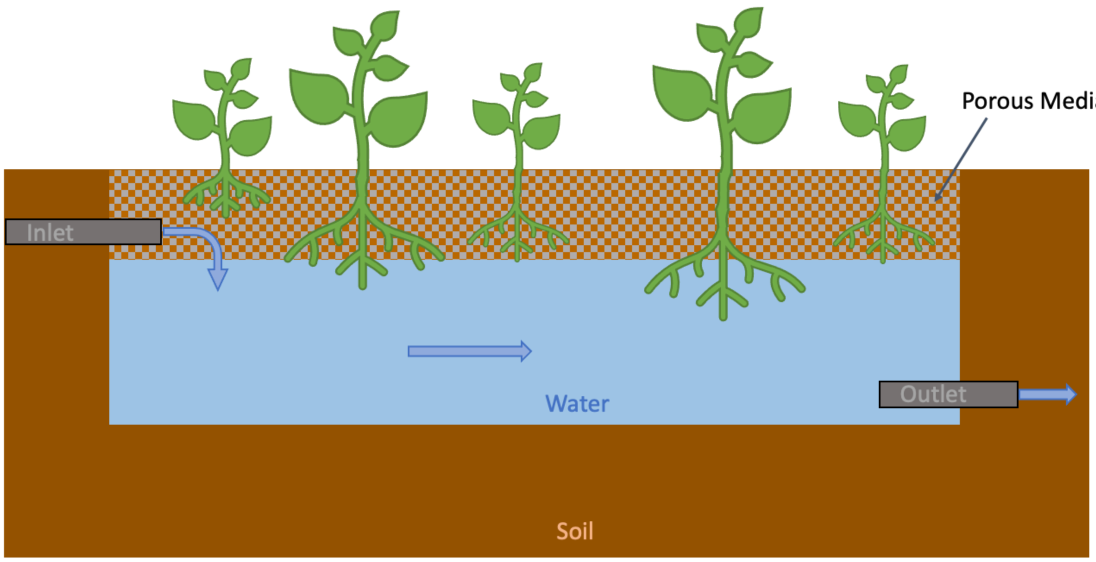

Figure 1: Diagram of a subsurface horizontal flow wetland

Subsurface horizontal flow wetlands are well adapted for wastewater treatment because it has more uniform flow conditions and less suspended solids which limits the clogging of the porous media (USEPA 1995a). It is also possible to use them for stormwater management.

Subsurface Vertical Flow

Subsurface vertical flow wetlands are similar to horizontal ones except that water flows vertically which reduces the area of the wetland because the long distance the water needs to travel is vertical instead of horizontal (Figure 2).

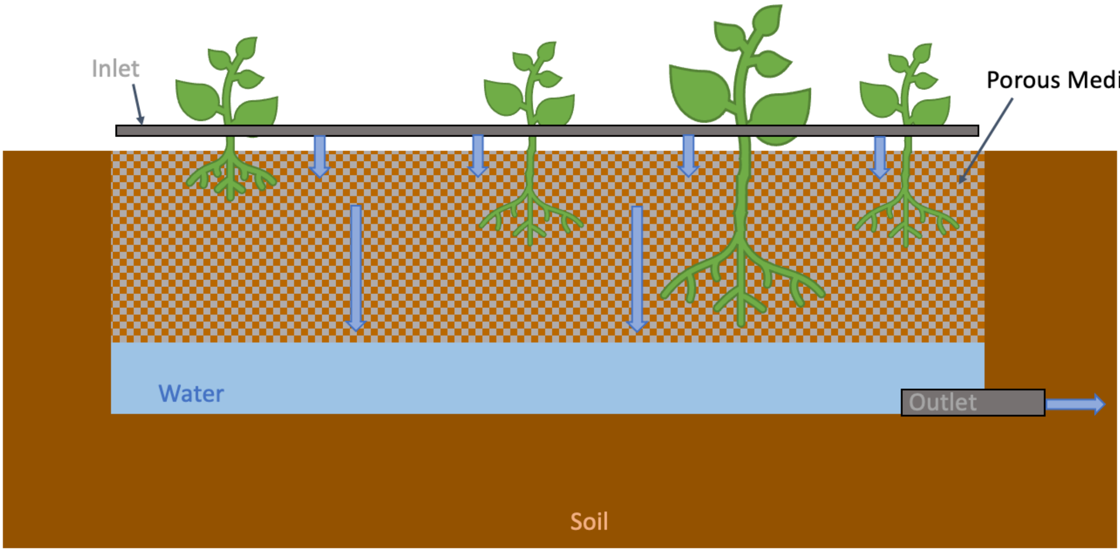

Figure 2: Diagram of a subsurface vertical flow wetland

In France, this is the preferred design for domestic wastewater treatment. To optimize even more the occupied area, water can flow through several basins. For example, a two stages vertical flow wetland often includes 3 parallel beds for the first stage and two parallel beds for the second (Troesch and Esser 2012).

Vertical flow wetlands have good performances in water treatment (Scholz 2006 Chapter 26, Dou et al 2017, Morvannou et al 2015) because they have a better assimilation potential per unit of area (USEPA 1995a). Because it is underground, this kind of wetland also has a better tolerance to cold, less issues with pest (mosquitos or muskrats for example), less evaporation and produces less unpleasant odors. However, they are more expensive to build, and their porous media needs to be replaced after several years because of clogging (CH2MHill 2014).

C. Review of current performances

Among the many purposes a constructed wetland can fulfill, we are interested in the stormwater management and water treatment.

For the former, the performances of a wetland can be evaluated as to how much stormwater it can take up and retain so that it can function even in the case of intense storm events and even if many events succeed to each other. The performances in terms of water retention depend directly on the design and sizing of the wetland so it is often not well monitored but rather a considered as a building constraint.

For treatment, performances are often evaluated as the removal rate of the different pollutants or the concentration in pollutants of the effluent - ie the water going out of the wetland. This concentration is compared to standards dictated by laws and that are made to limit the damages the pollutants can do to the environment or human health when released in receiving water.

This paper will thus focus on treatment performances. They are often studied because they are variable depending on the wetland design, local hydraulic and climatic conditions, and the pollutants to be treated and the variability in pollution concentrations. The current performances of constructed wetlands for various pollutants were evaluated through a literature review. As urban areas are the main interest in this paper, the pollutants considered are typical of urban runoff from surfaces and domestic wastewater (sediments, organics, nitrogen, phosphorus, heavy metals, de-icing salts, bacteria).

Sediments

Stormwater picks up a lot of dirt and particles between the moment it touches a surface and the moment it reaches the wetland. This high content of suspended solids decreases water quality. Wetlands are very good at dealing with suspended solids (Scholz 2006 Chapter 27, CH2MHill 2014, Dou et al 2017, Morvannou et al 2015) because they reduce water velocity thus encouraging their settling.

However, the issue with sediments is that they accumulate and clog the wetland. Most designs of wetland include a sediment forebay where most sediments can settle before a clearer water goes into the actual wetland (CH2MHill 2014). At the same time, the forebay removes contaminants that are adsorbed to the sediments. Maintenance of this forebay is necessary every few years to remove the sediments but this simple first step improves a lot the performance of the wetland and reduces its clogging.

Organics

Both runoff and wastewater contain organic pollutants like hydrocarbons. Those pollutants are characterized by their high content in carbon that can be detected by measuring the biological oxygen demand (BOD) or the chemical oxygen demand (COD) which represent the oxygen used by organisms or just for chemical reactions in general to decompose the pollutants. Wetlands are very efficient at carbon removal. Many observations and experiments showed that water from the outlet usually meets the legal water quality standards (Scholz 2006 Chapter 26, Scholz 2006 Chapter 27, CH2MHill 2014, Dou et al 2017, Morvannou et al 2015, Ho et al 2018).

Nutrients

Nutrients such as nitrogen and phosphorus come from fertilizers used in garden lawns, feces from domestic animals, and untreated domestic wastewater. Performances of wetlands are mixed (Dou et al 2017, Scholz 2006 Chapter 27) because they depend strongly on the concentration of the input (Morvannou et al 2015) and the design of the wetland. For example, a horizontal flow wetland would be more efficient for total nitrogen and phosphorus removal than a vertical flow wetland (Troesch and Esser 2012).

Heavy metals

Picked up on the roads and roofs by stormwater, heavy metals are very problematic as they can be very toxic for wildlife and aquatic organisms even in small doses. Unfortunately, constructed wetlands alone are not sufficient to decrease their concentration below standards (Scholz 2006 Chapter 24 & 26).

To solve that issue, it is possible to apply a more conventional treatment to the water to deal with the remaining metals or to dilute the outgoing water with clean water to artificially decrease the still hazardous concentrations. It is also possible to improve the performances of the wetland for metal remediation specifically. According to Scholz (2006 Chapter 26), increasing the pH of the water improved the removal of nickel because it encouraged the chemical reactions that made it react in the wetland. Plants resistant to metals can also be used to take in metals from the water and accumulate them into their tissues, which is called phytoremediation. This method can require a lot of maintenance. Frequent harvesting or replacement of the plants may be required because they can reach the maximum level of metal they can accumulate rather fast.

De-icing salts

From late autumn to the end of winter, roads are regularly covered with de-icing salts to prevent the formation of ice that could cause car accidents. However, they cannot be naturally decomposed but only accumulated in the wetland. If there is too much salt entering the wetland then it will be released in the effluent unattenuated (Scholz 2006 Chapter 26).

Synthesis:

To conclude, constructed wetlands can currently take care of a range of pollutants found in urban runoff and wastewater in a satisfactory manner. The results of the review are summed up below (Table 1).

Constructed wetlands are very efficient in dealing with sediments and organics and can be adequate for reducing nitrogen and bacteria. However, phosphorus can only be taken in a soluble form by plants and soil can only take insoluble forms up under specific conditions. Under reducing conditions, wetlands can release phosphorus over time. Heavy metals and de-icing salts present difficulties. For those, a supplementary treatment can turn out to be necessary. This can simply be the implementation of phytoremediation where plants accumulate the metals in their tissues.

	Simulated road runoff	Stormwater	Combined Stormwater Overflow	Domestic Wastewater	Overall Performance
Sediments (TSS)	4	1	2	2	Good
Carbon (COD or BOD)	1	1	2	1	Very Good
Nutrient (Total Nitrogen)	/	3	2	2	Moderate
Nutrient (Total Phosphorus)	/	4	/	5	Not Good
Heavy Metals	4	4	/	/	Not Good
De-icing salts	4	/	/	/	Not Good
Bacteria	/	2	/	/	Good

Table 1: Results of a literature review on 10 articles about different wetland's performances.

Scale of the table:
1: effluent always complies with regulation
2: effluent complies with regulation most of the time
3: part of the pollutant is treated enough for regulation but not the other (ex: nitrification but no denitrification)
4: pollutant is treated efficiently only until a threshold
5: effluent never complies with regulations

II. Climate change in France

A. Increased temperatures

Compared to pre-industrial levels, the average temperature in France has already increased by almost 1°C (NOIGW 2009). Because of the global emissions of greenhouse gas this trend is projected to continue in the future making France hotter all year long and especially in the summer (NOIGW 2009).

Vautard et al. (2019) found that because of that, heat waves have at least 5 times more chances to happen and are becoming more intense. It has already been felt through the major heatwaves of 2003, 2011 and 2019. More precisely, the heat wave that struck Europe in June 2019 would have been several degrees cooler a century ago (Vautard et al 2019). This is especially true in southern France because of its Mediterranean climate that encourages the loss of soil moisture which in return limits evaporative cooling and encourages even higher temperatures.

More than heat waves that impact mostly human health, it is droughts that can impact constructed wetlands. A drought is a natural phenomenon defined by an extensive and sustained lack of available water (ClimateChangePost 2021a). There are different types of droughts that can happen all at the same time: meteorological (lack of precipitation), hydrological (low stream flows and groundwater levels) and agricultural (insufficient soil water available during the growing season).

Because of increased temperatures and drier soils added to a decrease in summer precipitation in southern France, more droughts are expected in the future. More precisely, in the driest areas, the dry season - when most droughts happen - is projected to shift a month earlier. For the wettest areas, the dry season is projected to start earlier which would expand its total duration and the intensity of droughts would increase significantly (ClimateChangePost 2021a). Overall in France, it is expected that more droughts will happen, and they will be more intense, more widespread and potentially longer.

B. Changes in precipitation

Climate models can predict the evolution of average temperature with enough confidence to use the results but this is not the case for precipitation because weather patterns are way more complex and have randomness. Moreover, local events (impossible to catch in a global model), natural variability and topographic conditions cause complexities that are hard to model.

For precipitation, what is projected and already happening is the shift in elevation mountain regions from snow (nival) regime towards a pluvial (rain) dominated regime (NOIGW 2009). Glaciers are melting and withdrawing (CREA Mont-Blanc 2019) which can cause risks of floods, mud- and landslides. It also affects water availability due to an earlier shift in melting snow in the spring and less water availability during the longer summers.

Because of increased temperatures in the summer, streams are expected to have reduced flows and the total time in low-flow over one year is expected to increase (NOIGW 2009). The annual maximum high streamflow and high flow volumes have different trends spatially:

For the north of France especially the east (Alsace) they will increase, and in the south, especially in mixed snow-rain regimes and in the Pyrenees they will decrease (Giuntoli et al 2012).

Floods are often linked to precipitation and there are huge uncertainties on their future evolutions like there are for precipitation (ClimateChangePost 2021b). In high altitude areas like the Alps, more torrential floods are expected and in the country in general, more flash floods or urban floods will also emerge (ClimateChangePost 2021b). Urban areas are indeed expected to witness higher runoff volumes in general thanks to their development that increases the impervious surfaces. That combined with an increasing variability of runoff could have serious impacts on urban areas and create flood conditions during large storm events.

C. Synthesis

Among all the changes in climate that are probably going to affect France, many could impact a constructed wetland.

1. The **temperature increase** because the reactions happening in wetlands and the biological activity depend on the temperature.

2. The increase in frequency and intensity of **droughts and heat waves** can affect the hydrology of the wetland and also the health of the whole ecosystem. To understand the

impacts produced by this, we can analyze the impacts of a lack of water and/or soil moisture on the wetland.

3. Finally, **floods** can cause a dysfunction as wetlands are made to receive a maximum quantity of water and do not deal with the surplus. As soon as the wetland receives more than the maximum quantity of water or is water-saturated for longer than it has been made to manage, it can be considered as flooded. We will thus try to find the impacts of such a situation.

III. Impacts of climate change on constructed wetland performances

In order to understand the impacts of the climatic changes we identified above, we are going to study three different concrete examples of constructed wetlands located in different areas of France so that their climate is different.

A. Marcy l'Étoile

<u>The wetland:</u>

Located in the Southern half of France near the big city of Lyon, the constructed wetland of Marcy l'Étoile treats combined sewer overflow (CSO) which is the surplus of water from combined sewers that the treatment plant cannot deal with during major storm events. The water is thus a mix of domestic wastewater and stormwater runoff during large rain events.

The climate of the area is warm and temperate with monthly average temperatures ranging from 3°C to 22°C and even in the winter, temperatures do not go below 0°C. The annual average precipitation is around 1000 mm (Climate-Data).

It is a vertical flow wetland with only one stage composed of two filter beds in parallel. Water goes through only one at the time and the other rests to regenerate oxygen to maintain the aerobic conditions necessary for the wetland to perform well (Palfy et al 2017). The design is different from usual vertical flow wetlands because it has a permanently saturated layer at the bottom of the filter that is supposed to mitigate water stress in long dry periods. Aeration pipes above this layer allow the wetland to maintain proper oxygenation.

This constructed wetland was monitored for 3 years for many different types of pollutants. Palfy et al (2017) gives us a picture of the current performances of the wetland (Table 2).

Pollutant	Removal Rate	Treatment objective fulfilled (yes/no)
Sediments (TSS)	96%	Yes
Carbon (COD)	79%	Yes
Nitrogen (NH4-N)	72%	Yes
Phosphorus (PO4-P)	8%	No
Heavy metals	variable	Yes
Hydrocarbons (PAHs)	80 to 92%	Yes

Table 2: Summary of the performances of Marcy l'Étoile's constructed wetland (data from Palfy et al 2017)

Climate change impacts:

Because of its already warm climate, the area of Marcy will be strongly impacted by a temperature increase all year long (Figure 3) and it can be expected that one of the main climate issues will be more frequent and more intense droughts and heatwaves.

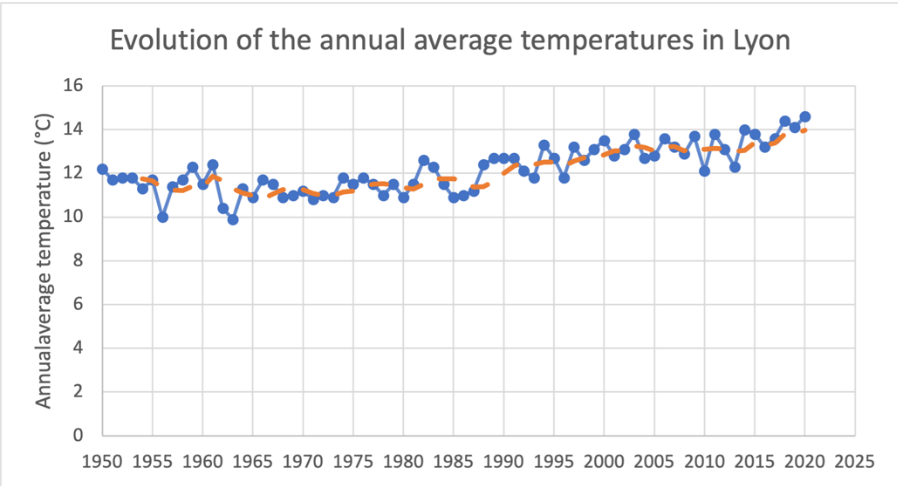

Figure 3: Annual mean temperature trend over 70 years near Marcy l'Étoile. The blue dots are the annual mean temperatures and the orange dotted line represents the moving average over 5 years that illustrates well an upward trend (source: infoclimat.fr)

The increase of temperature in the cold season (winter) can actually help improve the wetland's nitrification performances because the bacterial activity (like nitrification) will be less decreased by the cold. The effect of temperature on nitrification has indeed been observed often in constructed wetlands (Chang et al 2014, Prost-Boucle and Molle 2012, Xia et al 2020). For other pollutants like sediments (TSS), organic matter (COD) or bacteria (ex: E. Coli), temperature does not seem to affect the efficiency much (Rozema et al 2016, Prost-Boucle and Molle 2012).

Droughts lead to lack of water and low soil moisture (Wilson 2017) and also increase evapotranspiration if combined with high temperatures. The vegetation which is important in the treatment processes of the wetland would suffer from that which could decrease the performances of the wetland. Because of the warm climate of the area, this wetland would especially suffer from it and even more as it relies on large (rare) rain events to receive water (Figure 4). Organics (COD) removal could especially be impacted as the performance is reduced when evapotranspiration between rain events is high and no rain event happens in a long time (Palfy et al 2017).

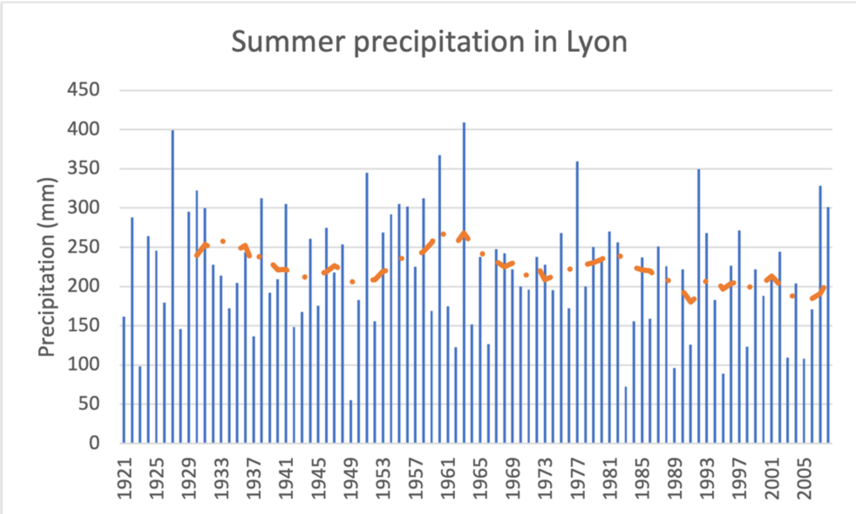

Figure 4: Trend of total precipitation over the summer period (June to August) near Marcy l'Étoile over 86 years.The orange dotted line is the moving average over 10 years and illustrates well a decrease in summer precipitation (source: Klein Tank et al 2002)

Finally, we need to consider that continuous urbanization over time will inevitably bring more impervious surfaces to the watershed and thus increase the runoff volume for stormwater. So even though flood risks are low the area of Marcy, the wetland could be impacted by too much runoff. The wetland will not be able to perform as well as possible if the inflow exceeds the design limit by too much (Arias Lopez 2013) so the overall performances could be reduced by that too.

To conclude, in a future climate, this wetland could see its overall performance negatively affected, especially if it is unable to maintain its vegetation cover (because of droughts). However, nitrogen removal through nitrification could be improved thanks to milder winter temperatures.

B. Challex

<u>The wetland:</u>

The constructed wetland of Challex has the same purpose as the previous one: treating combined sewer overflow. So it receives domestic wastewater and stormwater from an urban watershed (Arias Lopez 2013). However, it is special because it also receives water outside of rain events which is called “dry period” (Arias Lopez 2013).

Challex is located in the Alps at low altitude (525m). Precipitation follows a mixed pluvial-nival regime (precipitation is dominated by rain or snow according to the period) as can be expected in mountains at low altitudes. Annual precipitation is a little below 1000 mm. The climate is cold and temperate with negative temperatures in winter and reaching a maximum of 26°C in the summer (weatherspark).

The constructed wetland is a two stages vertical flow wetland with three filter beds in parallel for the first stage and two for the second. Because of the very intense rain events that can happen, the wetland has a tank to store incoming water if the inflow exceeds 3600m^3/h and treat it later. It is designed for an inflow of 100 m^3/h or 0,4 m/day in dry (no rain) period but it has proven to work well for up to 2,6 m/day (Arias Lopez 2013).

The most important pollutants for water from storm runoff and domestic wastewater were monitored for two years and a summary is showed Table 3:

Pollutant	Removal rate	Treatment objective fulfilled (yes/no)
Sediments (TSS)	91%	Yes
Carbon (COD)	86%	Yes
Nitrogen (TKN)	87%	Yes

Table 3: Summary of the performances of Challex's constructed wetland (data from Arias Lopez 2013)

Climate change impacts:

One important change in this mountainous area is the shift towards a more pluvial regime as winters get warmer and less snow falls. More rain instead of snow combined with early melting because of higher temperatures might produces higher peaks in runoff volumes every year. This affects the wetland in two ways. First, if the inflow is too high, the retention time of the water could decrease as water is entering the wetland more often in order not to be overwhelmed. Retention time is key to the efficiency of the treatment from the wetland so a shorter one could impact the overall performances of the wetland for the worst (CH2MHill 2014) and even lead to the release of partially treated water. Secondly, if water comes in continuously without letting time for the wetland to regenerate oxygen, then many reactions necessary for the treatment will not be possible which would make the wetland perform very badly (Arias Lopez 2013). All this could be exaggerated by the growth of the surrounding urban area and thus of impervious surfaces that will increase runoff volumes further.

Much like the previous wetland in Marcy l’Étoile, this one could see its nitrification performances increased by a milder climate (Figure 5). However, Arias Lopez (2013) noted that nitrification efficiency could be decreased above a certain volume of incoming water so the potential floods could negate the better nitrification.

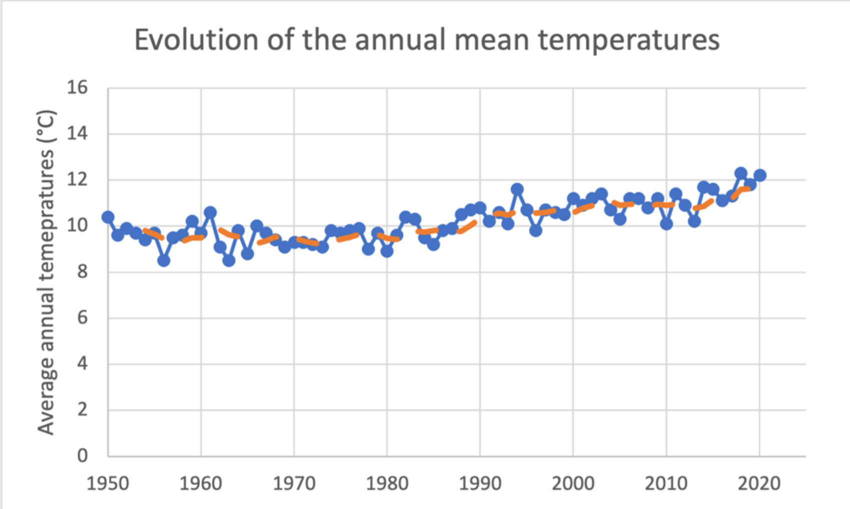

Figure 5: Annual mean temperature trend over 70 years near Challex. The blue dots are the annual mean temperatures and the orange dotted line represents the moving average over 5 years that illustrates well an upward trend (source: meteoswiss.ch)

Thanks to a colder climate and a high precipitation level, droughts and heatwaves should affect less the area. If they do, it will be in a similar way than for the previous wetland so an overall reduction of performances. But it might be mitigated by the regular inflow of water in this wetland even in "dry periods" that could help maintain vegetation.

In short, Challex's constructed wetland will probably be impacted by the future climate. Its performances could decrease lightly or even drastically if it is not able to allow its filter beds to regenerate enough oxygen. High volumes of water from floods or increased runoff are probably the biggest issue for this wetland.

C. Orly Airport

<u>The wetland:</u>

This wetland is located on the Northern half of France in the very dense urban area surrounding Paris. The climate is temperate with average monthly temperatures ranging from 4°C to 20°C. In winter, negative temperatures are frequent. Annual rainfall is 720 mm and evenly distributed over the year (monthly precipitation between 51 and 70 mm) (Climate-data b, meteoblue).

This wetland is special because it manages stormwater runoff from an airport. The water is similar to a road runoff with a lot of hydrocarbons and heavy metals. The main issue is that in winter, an important amount of de-icing products is used to allow planes to take off.

The wetland is a two stages vertical flow wetland preceded by a sedimentation pond. It has first been tested over two winters before being implemented at full scale. The performances from both the experiment (Branchu et al 2014) and the first year of full-scale functioning (Casteran 2015) are summed up (Table 4). As the pollutant of focus in those studies was mainly carbon (measured by Total Organic Carbon and Chemical Oxygen Demand), there are no figures given for treatment performances of other pollutants. However, the presence of a sedimentation pond should imply good removal performances for sediments. Other problematic pollutants found in road runoff and even more so in runoff from airports runways are metals. We will assume that if the removal rates of metals were largely inferior to the treatment objectives, the wetland would not have been built after the first experiment (Branchu et al 2014). So, it is expected that metals removal is not currently an issue in this wetland.

Pollutant	Removal rate (experiment - full scale 1st year)	Treatment objective fulfilled (yes/no)
Sediments (TSS)	not given	/
Carbon (COD)	85% - 89%	Yes
Carbon (TOC)	80 to 86% - 30 to 75%	Yes - variable
Nitrogen (TKN)	not given	/
Heavy metals	not given	(yes)

Table 4: Summary of the performances of Orly Airport's constructed wetland (data from Branchu et al 2014 and Casteran 2015)

Climate change impacts:

The same general impacts that were determined for the previous wetlands can be applied for this one: nitrification could be improved by milder temperatures (Firgure 6) but overall performances could decrease if more precipitation of floods, and more droughts happen.

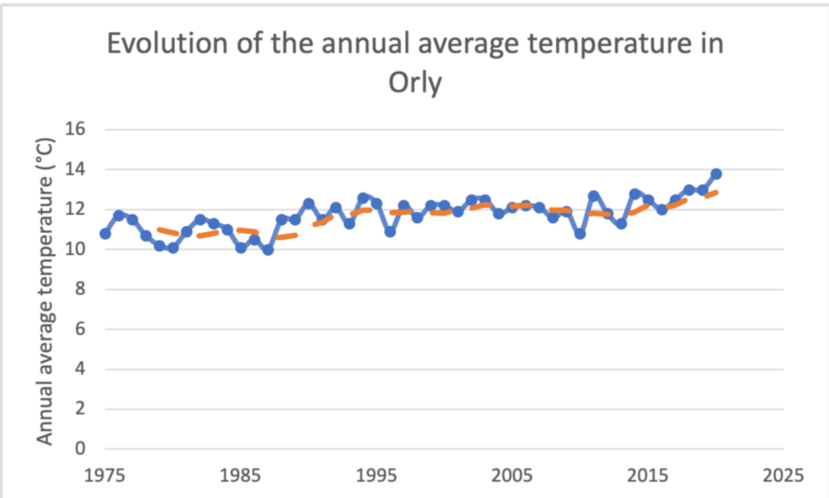

Figure 6: Annual mean temperature trend in Orly over 45 years. The blue dots are the annual mean temperatures and the orange dotted line represents the moving average over 5 years that illustrates well an upward trend (source: infoclimat.fr)

The area being a huge airport, its impervious surfaces would not evolve much in the future which means that an increase in the runoff will not be the main issue unless very intense storm become the norm. However, it is sensitive to droughts.

But the most interesting thing about this wetland is that its winter performances could increase thanks to warmer temperatures. Indeed, it currently has trouble reaching its treatment objectives in winter because of the de-icing products that are difficult to deal with. Hotter winters (Figure 7) also mean that less products are used so the treatment is done more easily.

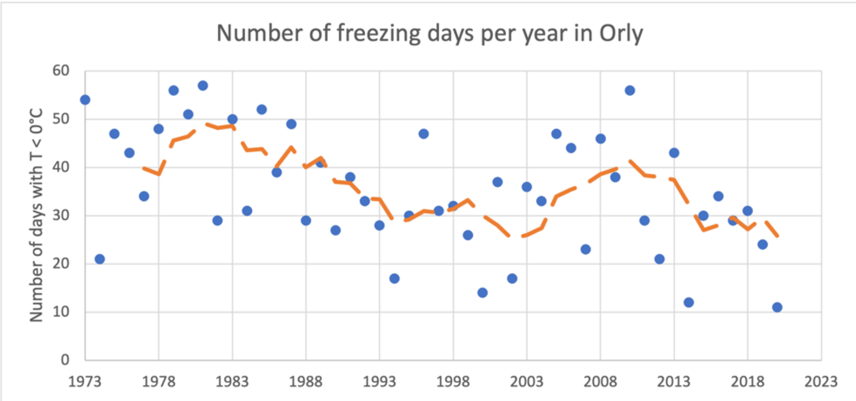

Figure 7: Evolution of the number of days when temperatures go below 0°C (so that water could freeze) per year in Orly since 1973. The orange dotted line is the moving average over 10 years and illustrates well the downwards trend (source: infoclimat.fr)

In conclusion, it is impossible to predict if the future climate will impact the performances of Orly's wetland for the better or for the worst. Mild temperatures in winter could improve nitrification and reduce the level of source pollution (de-icing products). However overall performances are exposed to the same risks as the others from increased runoff and droughts.

D. Synthesis:

Climate change will have an impact on the performances of constructed wetlands in water treatment. However, according to the current climate, and the pollutant of interest, this impact can be very different. It is difficult to tell with certainty if overall it will be negative or not.

1. Temperature increase: Winter performances could benefit directly and indirectly from mild temperatures. It could lead to a boost in biological activity, especially in the colder regions in the North and the mountains. It could also improve treatment performances by reducing source pollution, for example by decreasing the consumption of de-icing products. However negative effects come from increased temperatures like those of droughts and heatwaves.

2. Droughts and heatwaves: More frequent and intense droughts could strongly decrease global performances of the wetlands in the dry season (end of spring and summer). Their impacts may be even worse in already warm climates like the Mediterranean region.

Maintaining the vegetation will be a crucial issue to keep the wetland functioning as plants are a main actor in both infiltration and treatment processes. The lack of soil moisture and the poor health of the vegetation could affect the infiltration (Wilson 2017) and treatment capacity of the wetland. As a result, droughts could reduce overall performances of the wetland with a gravity depending on the gravity of vegetation deterioration. Plus, the increased evapotranspiration added to long periods without rain could specifically decrease organics removal (Palfy et al 2017).

3. Floods: Changes in precipitation and flood intensity and frequency would also impact constructed wetlands. Too much water at the inflow could lead to the release of untreated or partially treated water. Urbanization accentuates this effect with impervious surfaces creating even more runoff in urban areas. So, urban areas and flood-prone areas like mountains would be strongly touched by those changes. Furthermore, subsurface flow wetlands would be particularly affected by longer water-saturated conditions as they need time without water to regenerate the oxygen in the porous material (Arias Lopez 2013). Overall, urban area constructed wetlands have a high risk of seeing their performances reduced by the high inflow from intense rain events and floods.

Finally, it is important to consider that all these impacts will happen together and the combined effects could be more complicated than just the sum of the separate impacts. It is difficult to predict the net effect on wetland's performances given these interaction processes. However, some performances will likely be reduced as a result of climate change and mitigating processes need to be considered.

IV. Mitigation of the impacts

The impact of climate change on the performances of constructed wetlands is not simple to analyze but it is likely significant and could lead to insufficient treatment of stormwater and domestic wastewater. It is necessary to find ways to mitigate it. For that, some possibilities already exist. As different climates and water sources imply different impacts, the mitigation solutions have to be adapted to them.

<u>In warm climates:</u>

What is most important to mitigate in warm climates is the lack of water and the effects of droughts. For that, it is possible to adapt the design of the wetland to make it more resistant to the lack of water. Resizing wetlands to smaller surfaces can prevent the loss of some water through evapotranspiration. It is also recommended to choose a subsurface flow wetland rather than a surface one because they will also lose less water to evaporation and thus resist dry seasons better.

Constructed wetlands still have to be a minimal size to deal with the water that comes during large rain events so those design changes are limited. To complement them, it could be useful to choose carefully the vegetation planted on the wetland. Drought-resistant and local plants such as *Euphorbia characias* (Mediterranean spurge) would improve the performances of the wetland during the dry season by ensuring a better survival of the vegetation.

Finally, it is possible to bring water to the wetland during the dry season and droughts to fight the lack of water and maintain the vegetation. To do that, there are several possibilities. If there are freshwater resources - like a lake, a river or groundwater - available nearby, then they could be used. However, it is necessary to first make sure that taping into those resources will not be detrimental to other uses (irrigation, environmental needs, etc.). Grey water could also be used. For example, water from combined sewers could be fed to the wetland during the dry season. This allows the wetland to maintain moisture levels while not depleting freshwater resources.

<u>In flood-prone areas:</u>

In areas that will receive huge amounts of stormwater runoff and areas with high risks of floods, mitigation should focus on increasing the ability of the wetland to take in large amounts of water.

As opposite to the previous situation, in this case, bigger wetlands would be more adequate. Surface flow wetlands could be better because they can receive large amounts of water without enduring dysfunctions which make them more adapted to flood-prone areas. With the same idea, building larger sedimentation ponds before the wetland could help mitigate large water inflow and also absorb the surplus of sediments that come with increased runoff and floods. It is important to notice that a regular maintenance of the pond (unclogging) is necessary to its proper functioning.

If the wetland is a subsurface flow wetland, then having more filter beds in parallel could make them more resilient because it would allow the beds to regenerate oxygen in turns while still managing large volumes of water.

Finally, a temporary storage system before the wetland could act as a safety measure for extreme floods. The surplus that the wetland cannot take could be kept in the storage system and released only when the wetland is ready to receive it.

<u>For road runoff with high metal content:</u>

In the case of water containing pollutants that are difficult to treat like heavy metals, different solutions are possible.

Phytoremediation can help treat metals and improve the decreasing performances of the wetland. To use this solution, the vegetation of the wetland must be chosen carefully to be effective in metal uptake and resistant to high pollution concentrations. Plants like *Brassica juncea* (Indian mustard) or *Eichhornia crassipes* (water hyacinth) could be used depending on the climate (current and future) of the area. Water hyacinth for example require much water so they would not be adapted to warm climates.

If no other solution gives satisfactory results, the current method is to dilute the water with clean water to decrease the pollutant levels below legal standards. Some have also tried to loop the water back into the wetland so that it could be treated twice which improved sediment and carbon (COD, BOD) removal (Prost-Boucle and Molle 2012).

Recommendations

We discovered that the impacts of climate change on performances of the wetlands are complex and their cumulative effect cannot simply be deduced by adding the separate impacts. Some mitigation strategies can be put in place but for them to be efficient, more research is needed both on the climate change and on the processes that affect the performances of constructed wetlands. It would be especially useful to study the cumulative impacts of future climates on wetlands and what mitigation strategies are best to counter them.

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