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IMPACT OF CLIMATE CHANGE ON URBAN WASTEWATER QUANTITY AND QUALITY

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ABSTRACT

This paper presents a possible trend in changes to the quantity and quality of wastewater resulting from changing climatic conditions in urban areas. Climate change significantly affects both the availability and characteristics of water resources, and consequently has a direct impact on the quantity and quality of urban wastewater. Through a comprehensive and systematic analysis of the system components, comprising both structural and non-structural elements, and their conceptualization, a framework was developed for constructing an integrated model of wastewater quantity and quality.

The study applies an existing model developed for the City of Mostar (UVS_MO Model), which was adapted for the analysis, presentation, and optimization of urban water system operation. The modelling methodology is based on ***Object-Oriented Modelling (OOM)*** *as a tool for the sustainable management of urban wastewater drainage systems, incorporating all dimensions of sustainability, including technical, economic, legal, social, and environmental aspects.*

Based on observed trends in key climate change indicators and projected future developments for the period ***2025–2050****, the study evaluates both the current* *performance of the drainage system and the expected changes in wastewater quantity and quality. The adopted modelling approach, combining simulation of the real system, object-oriented modelling, and* ***"what-if" scenario analysis****, proved to be an effective and reliable tool for supporting the sustainable planning, operation, and management of urban drainage systems.*

The proposed model and methodology are suitable for the analysis and broader application to complex urban water systems, particularly under the challenges imposed by ongoing global climate change.

Keywords: Drainage, wastewater treatment, object oriented modeling, sustainable development. climate Change

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1. INTRODUCTION

Wastewater drainage and sewerage constitute a subsystem of the complex urban water system. The management of these infrastructure components is a highly demanding and complex task, as it must meet all requirements related to the drainage needs of water-service users (water supply), i.e., the collection and conveyance of all used wastewater to the receiving water body (recipient). In doing so, a number of conditions and constraints related to system capacity, wastewater transport, socio-economic and social aspects must be satisfied, without adversely affecting the natural environmental characteristics of the water regime or the natural ecosystem. When stormwater is also incorporated into the system, it becomes a complex hydraulic engineering system that requires optimal and functional management.

The objective is to achieve the highest possible and sustainable level of performance and reliability of the drainage system with respect to all key parameters. This includes the following:

- collection of all wastewater flows (sanitary wastewater and stormwater);
- conveyance of wastewater to the wastewater treatment plant;
- treatment of the collected wastewater; and
- discharge of treated effluent into the receiving water body.

This paper presents and analyses the structure and characteristics of the potential impacts of climate change on urban wastewater and subsequently applies contemporary modelling tools to simulate the operation of urban drainage systems. To present and illustrate potential changes within the urban water system, **Object-Oriented Modelling (OOM)** is applied using an existing object-oriented model [18], originally developed for the sustainable management of the entire urban water system. Changes in wastewater conditions are analysed with respect to all major influencing components that may undergo significant changes as a consequence of climate change.

The principal climate-related factors affecting urban water systems include **increasing temperatures, changes in precipitation patterns, more frequent flooding, prolonged drought periods, sea-level rise (in coastal cities), and deterioration of water quality**. These changes require the adaptation of urban water systems in order to enhance their resilience to climate change.

As a case study for the simulation of system operation and management, the wastewater sewerage system of the **City of Mostar, Bosnia and Herzegovina (BiH)**, is considered. Accordingly, the objective is to identify and illustrate the potential impacts of climate change and, by means of an appropriate modelling tool, analyse possible trends in these impacts and identify potential operational difficulties within the wastewater drainage system.

By simulating the operation and optimal management of a complex urban wastewater drainage system, it is possible to obtain an integrated assessment of climate-related impacts and to identify the most significant influencing parameters. The simulation results provide a basis for further system analysis and for identifying where and how improvements in system performance can be achieved.

Changes in the **quantity and quality of urban wastewater** result from the interaction of various influencing parameters. These parameters should therefore be clearly defined and evaluated through **sensitivity analysis**, providing a basis for developing guidelines and recommendations aimed at improving system performance within the framework of sustainable development.

The methodological approach used to assess the condition and operation of the wastewater drainage system is based on **systems analysis**, which provides a rational framework for decision-making and for solving complex problems associated with the planning, operation, management, and adaptation of urban wastewater systems.

2. POTENTIAL IMPACTS OF CLIMATE CHANGE ON URBAN WASTEWATER

Climate change, in a general sense, refers to long-term changes in the Earth's average climatic conditions, including air temperature, the amount and distribution of precipitation, the frequency of extreme weather events, and the state of the oceans and ice cover. Although the climate has changed naturally throughout geological history, current changes are occurring at a considerably faster rate and are largely driven by human activities, primarily fossil fuel combustion, deforestation, and land-use change. These activities increase atmospheric concentrations of greenhouse gases, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), thereby intensifying the natural greenhouse effect and contributing to global warming.

The principal global drivers of climate change include:

- greenhouse gas emissions from the energy, industrial, transport, and agricultural sectors;
- deforestation, which reduces the capacity of ecosystems to sequester carbon dioxide;
- intensive agriculture, particularly methane emissions from livestock production and rice cultivation; and
- urbanisation and land-use changes that affect local and regional climatic conditions.

Climate change has significant implications for urban wastewater systems, including sewer networks and wastewater treatment plants (WWTPs). The most important climate-related factors affecting these systems include:

- more intense and frequent precipitation;
- prolonged drought periods;
- rising temperatures;
- more frequent extreme weather events;
- sea-level rise in coastal areas; and
- changes in wastewater quality.

2.1. More Intense and Frequent Precipitation

One of the most pronounced consequences of climate change is the alteration of precipitation regimes, with short-duration but highly intensive rainfall events becoming increasingly important. Although total annual precipitation does not necessarily increase substantially, its distribution throughout the year is becoming more irregular. Prolonged dry periods may be interrupted by high-intensity rainfall events that deliver large volumes of water within a short period. Such changes pose a serious challenge to urban water management because existing drainage systems were generally not designed to accommodate these increasingly severe stormwater loads.

Climate projections for Bosnia and Herzegovina and Southeast Europe indicate an increasing importance of extreme precipitation events, particularly during transitional seasons. Instead of evenly distributed rainfall, high-intensity storm events may occur over relatively short periods, generating exceptionally large rainfall volumes [1].

The main consequences of such precipitation patterns include:

- increased surface runoff;
- reduced infiltration into the soil;
- rapid increases in water levels in urban watercourses;
- increased risk of flash flooding; and
- increased soil erosion and sediment transport.

In urban areas, these problems are further intensified by the high proportion of asphalt, concrete, roofs, and other impervious surfaces, which substantially reduce natural infiltration.

Most existing sewerage systems were designed using historical rainfall records and corresponding design criteria. Under changing climatic conditions, current and future rainfall intensities may exceed the design capacity of individual system components.

When stormwater inflow exceeds the hydraulic capacity of pipes and collectors, the consequences may include:

- surface flooding of streets and roads;
- flooding of underpasses, basements, and garages;
- damage to roads and municipal infrastructure;
- disruption of traffic; and
- increased rehabilitation and maintenance costs.

The problem is particularly pronounced in cities with **combined sewer systems**, where stormwater and sanitary wastewater are conveyed through the same network.

Urban flooding differs from conventional river flooding because it can develop very rapidly, sometimes within several tens of minutes after the onset of an intense rainfall event.

Due to the high proportion of impervious surfaces, a large fraction of precipitation is transformed into direct runoff entering the sewer network or flowing towards topographically lower parts of the city.

The most common consequences of urban flooding include:

- risks to public safety;
- damage to residential and commercial buildings;
- disruption of public services;
- damage to electricity and transport infrastructure; and
- increased infrastructure maintenance and insurance costs.

Densely developed urban centres with limited green and permeable areas are particularly vulnerable.

In combined sewer systems, intense rainfall causes a rapid increase in the flow conveyed towards wastewater treatment plants. The resulting impacts may include:

- hydraulic overloading of wastewater treatment plants;
- reduced treatment efficiency;
- combined sewer overflows (CSOs); and
- discharge of partially treated or untreated wastewater into receiving waters.

Such events increase the risk of microbiological contamination of surface waters and may have adverse effects on human health and aquatic ecosystems.

Intense rainfall also washes considerable quantities of pollutants from urban surfaces into drainage systems. Stormwater runoff may contain [3]:

- oils and fuels originating from road surfaces;
- heavy metals;
- microplastics;
- suspended solids; and
- residues of pesticides and other chemicals.

These pollutants may eventually enter rivers and lakes, deteriorating water quality and potentially increasing the complexity and cost of drinking-water treatment.

2.2. Prolonged Drought Periods

Longer and more frequent drought periods represent another important consequence of climate change with substantial implications for urban water management. Climate projections for Bosnia and Herzegovina indicate that the duration and intensity of drought conditions may increase during the 21st century, particularly during the summer months. At the same time, rising air temperatures increase evapotranspiration, while precipitation during the warmer part of the year may decrease or become concentrated into shorter and more intensive events. The resulting effects include reduced availability of water resources and increased pressure on water supply, sewerage, and wastewater treatment systems [4].

Reduced availability of water resources

During drought periods, river discharges and lake levels decrease. Consequently, the dilution capacity of receiving waters is reduced, which may lead to increased concentrations of:

- organic pollutants;
- nutrients, particularly nitrogen and phosphorus;
- heavy metals; and
- microorganisms.

At the same time, higher water temperatures reduce dissolved oxygen concentrations, further deteriorating the ecological status of receiving waters and creating favourable conditions for the proliferation of algae and cyanobacteria.

Impact on wastewater treatment plants

Prolonged dry periods also affect the characteristics of wastewater entering treatment plants. With lower stormwater and infiltration contributions, wastewater may become more concentrated.

This may result in:

- increased organic and nutrient loads per unit volume;
- changes in biological treatment processes;
- increased aeration requirements and associated energy consumption; and
- the need to adapt plant operation to increasingly variable influent conditions.

During prolonged drought periods, inflows to rivers, lakes, and reservoirs decrease, while groundwater levels may also decline. Since many cities in Bosnia and Herzegovina rely on groundwater sources or surface watercourses for drinking-water supply, prolonged drought may reduce source yields and compromise the reliability of water supply.

The main consequences include:

- reduced river and stream flows;
- declining groundwater levels;
- reduced yields of drinking-water sources;
- increased risk of water shortages during the summer months; and
- increased competition among domestic, industrial, and agricultural water demands.

In urban areas, where water demand is relatively high, drought periods may lead to water-use restrictions and require additional water-resource management measures. During hot and dry periods, water demand may increase because of:

- increased household water use;
- irrigation of parks and urban green areas;
- operation of industrial cooling systems; and
- increased water consumption in tourist areas.

At the same time, available water resources decrease, placing additional pressure on public water-supply systems and potentially resulting in reduced network pressure or temporary restrictions on water consumption.

Drought periods also affect sewer network operation. Reduced wastewater flows can result in lower flow velocities, thereby promoting the deposition of sand, sludge, and other solids.

The consequences may include:

- sewer blockages;
- increased maintenance costs;
- more frequent sewer flushing requirements; and
- reduced hydraulic efficiency of the network.

Furthermore, lower flow velocities and longer wastewater residence times can promote organic matter degradation under anaerobic conditions, potentially contributing to odour problems and the formation of undesirable compounds within the sewer network.

2.3. Increase in Air and Water Temperature

The increase in average air temperature is one of the clearest indicators of climate change and directly affects urban water systems. Higher temperatures modify the hydrological cycle, influence surface-water and groundwater quality, and increase pressure on water infrastructure.

Higher air temperatures intensify evaporation from rivers, lakes, reservoirs, retention basins, and soils. As a consequence:

- the availability of surface-water resources decreases;
- water levels in reservoirs used for water supply may decline;
- inflows to watercourses may decrease during the summer months; and
- dependence on groundwater abstraction may increase.

In urban areas with high water demand, increased evaporation and evapotranspiration may place additional pressure on public water-supply systems, particularly during prolonged heat waves.

One of the most important consequences of increasing water temperature is a reduction in dissolved oxygen concentrations. Warmer water has a lower capacity to retain dissolved oxygen, which may result in [6]:

- lower dissolved oxygen concentrations;
- adverse effects on fish and other aquatic organisms;
- increased potential for anaerobic processes; and
- development of unpleasant odours.

At the same time, higher temperatures favour the growth of algae and cyanobacteria, potentially leading to harmful algal blooms. Such events may cause:

- increased water turbidity;
- production of toxins harmful to humans and animals;
- increased drinking-water treatment requirements and costs; and
- reduced recreational value of rivers and lakes.

From the perspective of wastewater management, temperature increases are also important because biological and biochemical processes within sewer networks and wastewater treatment plants are temperature-dependent. Consequently, changes in wastewater temperature may affect oxygen consumption, organic matter degradation, microbial activity, odour formation, and treatment efficiency.

2.4. More Frequent Extreme Weather Events

A warmer atmosphere can retain more water vapour, creating conditions that may contribute to more intense precipitation events. At the same time, longer periods without precipitation may occur, resulting in an increasingly pronounced alternation between dry periods and intense rainfall events. Such climatic variability makes the planning, design, and management of urban water infrastructure more demanding.

Extreme weather events of particular relevance to Bosnia and Herzegovina include:

- short-duration intense rainfall;
- flash floods in urban areas;
- large-scale river floods;
- prolonged summer droughts;
- heat waves;
- landslides triggered by soil saturation; and
- severe storms accompanied by intense rainfall.

Flash floods can develop rapidly, sometimes within approximately one hour following the onset of intense precipitation. In urban areas, infiltration is strongly reduced by asphalt, concrete, roofs, and other impervious surfaces. Consequently, stormwater is rapidly transformed into surface runoff and conveyed towards drainage systems and low-lying areas.

The principal consequences of flash flooding include:

- risks to human life and public safety;
- damage to residential and commercial buildings;
- disruption of transport and public services;
- failure or damage of electricity and telecommunications infrastructure; and
- substantial economic losses.

Urban areas located along small watercourses, torrents, and drainage channels are particularly vulnerable [3].

Overall, the combined effects of **intense precipitation, prolonged drought, increasing temperatures, and extreme weather events** can significantly alter both the **quantity and quality of urban wastewater**. These effects are interrelated: intense rainfall may cause rapid hydraulic loading and dilution of wastewater, whereas prolonged hot and dry periods may reduce sewer flows and dilution, thereby increasing pollutant concentrations. Consequently, climate change should not be considered as a single external factor but as a set of interacting drivers affecting sewer hydraulics, wastewater characteristics, treatment processes, receiving-water conditions, and the overall reliability and resilience of urban wastewater systems.

2.5. Changes in Wastewater Quality

Climate change affects not only the quantity of wastewater but also its physical, chemical, and biological characteristics. Changes in temperature, precipitation patterns, and the frequency and intensity of extreme weather events alter pollutant concentrations, hydraulic loading of sewer systems, and the performance of wastewater treatment plants (WWTPs). These changes may result in greater operational challenges, increased maintenance costs, and a higher risk of pollution of receiving water bodies, including rivers, lakes, and coastal waters.

Short-duration, high-intensity rainfall events can cause a rapid inflow of large volumes of stormwater into sewer systems, particularly in urban areas served by combined sewer systems, where sanitary wastewater and stormwater are conveyed through the same network.

The principal consequences include:

- dilution of wastewater;
- rapid increases in influent flow to wastewater treatment plants;
- hydraulic overloading of treatment facilities;
- reduced hydraulic retention time within treatment processes; and
- reduced pollutant removal efficiency.

Under such conditions, wastewater treatment plants may be unable to achieve their design treatment performance because biological treatment processes require sufficient contact time between microorganisms and wastewater.

When the incoming flow exceeds the hydraulic capacity of the sewer network or wastewater treatment plant, combined sewer overflow (CSO) events may occur.

These events can result in [4]:

- discharge of untreated or partially treated wastewater into receiving waters;
- increased concentrations of faecal bacteria and viruses;
- deterioration of surface-water quality;
- increased risks to public health; and
- temporary restrictions on bathing and recreational water use.

The potential importance and frequency of such events may increase as extreme precipitation becomes more intense.

During drought periods, the amount of stormwater entering sewer systems decreases considerably, while sanitary wastewater generation may remain relatively stable. Consequently, wastewater can become more concentrated, potentially resulting in:

- increased concentrations of organic pollutants;
- higher nitrogen and phosphorus concentrations;

- increased concentrations of suspended solids;
- increased chemical oxygen demand (COD); and
- increased five-day biochemical oxygen demand (BOD_5).

More concentrated wastewater increases the pollutant load imposed on treatment processes and may require adjustments to plant operation and process control.

Higher temperatures accelerate biological and chemical processes within sewer systems. Potential consequences include:

- accelerated degradation of organic matter;
- increased hydrogen sulphide (H_2S) formation;
- increased occurrence of unpleasant odours;
- accelerated corrosion of concrete and metallic sewer infrastructure; and
- changes in microbial activity within biological treatment processes.

Although moderately higher temperatures may enhance certain biological processes, excessive warming can adversely affect process stability and alter the performance of microbial communities involved in nutrient removal, particularly nitrogen and phosphorus transformations.

Changes in Microbiological Quality

Climate change may also affect the microbiological characteristics of wastewater. During intense rainfall and flooding, increased mobilisation and transport of microbiological contaminants may occur, including:

- faecal bacteria;
- viruses;
- protozoa; and
- other pathogenic microorganisms originating from flooded or contaminated areas.

Higher temperatures may also modify the survival, persistence, and growth conditions of certain microorganisms in wastewater and receiving environments. Consequently, the discharge of untreated or insufficiently treated wastewater may increase microbiological risks to receiving waters and public health.

Emerging Contaminants

An increasingly important challenge is associated with emerging contaminants, including:

- pharmaceutical residues and antibiotics;

- hormones;
- personal care products;
- microplastics;
- per- and polyfluoroalkyl substances (PFAS), often referred to as “forever chemicals”;
- pesticides; and
- industrial chemicals.

Climate-related changes in precipitation, runoff, temperature, wastewater flow, and dilution may influence the concentrations, mobilisation, and transport of these contaminants through urban drainage systems. Furthermore, many conventional wastewater treatment plants were not originally designed to achieve complete removal of these substances.

Impact on Wastewater Treatment Plant Performance

Changes in both wastewater quantity and quality make stable wastewater treatment plant operation more difficult. The most common operational challenges include:

- highly variable hydraulic loading;
- fluctuations in influent pollutant concentrations and loads;
- instability of biological treatment processes;
- increased energy demand, particularly for aeration;
- changes in sludge production; and
- more frequent requirements for operational adjustment and process optimisation.

Wastewater treatment plants designed according to historical climatic and hydraulic conditions may therefore require technological upgrades, capacity improvements, process optimisation, or reconstruction to maintain adequate treatment performance under future climate conditions.

In general, it can be concluded that climate-induced changes in the characteristics and condition of urban wastewater may be substantial, highly variable, and, in some cases, extreme. An important feature of these impacts is the contrast between wet-weather conditions, characterised by high hydraulic loads and wastewater dilution, and hot and dry conditions, characterised by lower sewer flows, reduced dilution, longer residence times, and potentially higher pollutant concentrations. Consequently, both hydraulic and pollutant loading should be considered when assessing the response of urban wastewater systems to climate change [1].

Changes in wastewater quality may have numerous adverse environmental and operational consequences, including:

- deterioration of river and lake water quality;
- increased eutrophication risk due to nutrient inputs;
- reduction in dissolved oxygen concentrations in receiving waters;
- adverse impacts on aquatic ecosystems;
- increased drinking-water treatment requirements and costs; and
- reduced potential for the safe reuse of treated wastewater.

Therefore, the assessment of climate-change impacts on urban wastewater should integrate changes in wastewater quantity, pollutant concentrations, pollutant loads, hydraulic conditions, treatment efficiency, and receiving-water quality. Such an integrated approach provides a more appropriate basis for modelling future system behaviour, identifying critical parameters through sensitivity analysis, and developing adaptation measures aimed at increasing the resilience and sustainability of urban wastewater systems.

3. IMPACT OF CLIMATE CHANGE ON WASTEWATER CONDITIONS IN BOSNIA AND HERZEGOVINA

The most important climate-change-related factors affecting Bosnia and Herzegovina (BiH) include:

- increasing average air temperatures and more frequent heat waves;
- changes in precipitation patterns, characterised by longer dry periods combined with more intense short-duration rainfall events;
- more frequent floods, flash floods, erosion, and landslides;
- reduced summer river flows and increased pressure on springs and groundwater resources; and
- increasing risks to agriculture, forests, human health, hydropower production, and biodiversity.

For urban water systems, these changes imply that sewer networks and wastewater treatment plants (WWTPs) will increasingly be required to operate under more variable and extreme hydrological and climatic conditions. During intense rainfall events, combined sewer systems may become hydraulically overloaded, potentially resulting in the discharge of untreated or partially treated wastewater into receiving waters. Flood events can also damage sewer collectors, pumping stations, and wastewater treatment infrastructure. In contrast, prolonged drought periods reduce river flows and consequently decrease the dilution and assimilative capacity of receiving water bodies.

Urban wastewater in Bosnia and Herzegovina typically contains organic matter, nutrients such as nitrogen and phosphorus, pathogenic microorganisms, detergents, microplastics, and residues of pharmaceuticals and other emerging contaminants. When wastewater is discharged without adequate treatment, the potential consequences include:

- deterioration of the quality of rivers, groundwater resources, and drinking-water sources;
- reduction in dissolved oxygen concentrations and adverse effects on aquatic organisms;
- eutrophication, including excessive algal growth and degradation of aquatic ecosystems;
- increased public-health risks during floods and human contact with contaminated water; and
- increased drinking-water treatment costs, as well as potential adverse effects on tourism and economic activities.

The relationship between climate change and wastewater management is bidirectional. Climate change increases the complexity of wastewater collection, conveyance, treatment, and discharge, while the wastewater sector itself can contribute to greenhouse gas emissions, particularly methane (CH_4) and nitrous oxide (N_2O). Therefore, climate-resilient wastewater management should address both adaptation to changing climatic conditions and mitigation of greenhouse gas emissions associated with wastewater treatment.

Priority measures for Bosnia and Herzegovina should therefore include the expansion and rehabilitation of sewer networks, reliable operation and upgrading of wastewater treatment plants, separation of stormwater and sanitary wastewater where technically and economically feasible, construction of retention and detention facilities, implementation of green infrastructure and sustainable urban drainage solutions, reduction of water losses, energy-efficient wastewater treatment, and recovery and utilisation of biogas where appropriate.

Bosnia and Herzegovina is particularly sensitive to these challenges because urban and industrial wastewater pressures, groundwater vulnerability, uneven wastewater infrastructure development, and climate-related hydrological changes interact and may jointly affect the long-term sustainability of water resources. Consequently, climate change should be incorporated into the planning, design, operation, and optimisation of urban wastewater systems rather than treated solely as an external environmental factor.

From the perspective of wastewater-system modelling, the effects of climate change can be represented through several interconnected pathways. Increasing temperatures and prolonged droughts may reduce wastewater and infiltration flows while increasing pollutant concentrations due to reduced dilution. In contrast, intense precipitation events may substantially increase stormwater inflow into combined sewer systems, resulting in higher total sewer flows but temporarily lower pollutant concentrations due to dilution. At the same time, extreme rainfall may increase pollutant loads through urban runoff and increase the probability of combined sewer overflows and hydraulic overloading of wastewater treatment plants.

Accordingly, an integrated assessment should consider simultaneous changes in wastewater quantity, BOD_5 and other pollutant concentrations, pollutant loads, stormwater inflow, infiltration and inflow (I/I), sewer-system capacity, treatment-plant performance, and receiving-water conditions. Such an approach enables the identification of the most sensitive components of the urban wastewater system and provides a basis for evaluating adaptation measures under different climate-change scenarios [15].

The following section presents graphical and illustrative representations of selected climate-change components and their potential impacts on wastewater quantity and quality in Bosnia and Herzegovina. These representations provide the basis for subsequent modelling and simulation of the urban wastewater system under changing climatic conditions.

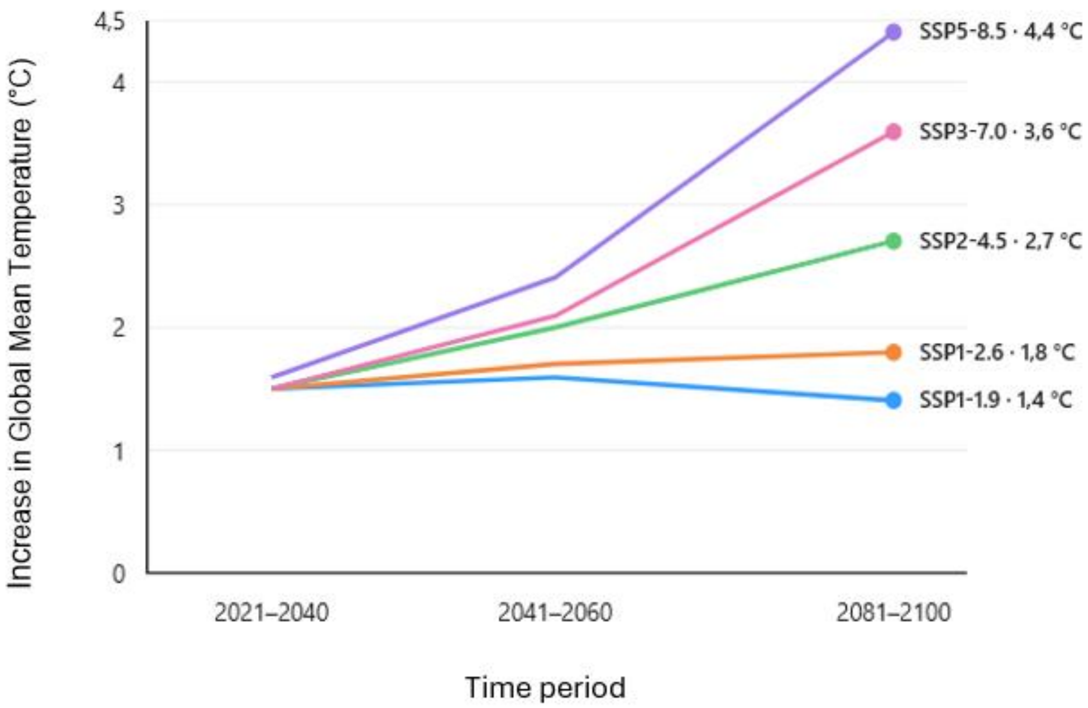

Figure 3.1. Projected Increase in Global Mean Surface Temperature under the Five IPCC AR6 SSP Scenarios Relative to 1850–1900 (2025–2050) [**1**]

For the purposes of this study, it is important to note that the IPCC AR6 provides official projections for 20-year periods, specifically **2021–2040** and **2041–2060**, rather than for the individual 2025–2050 planning period. For 2021–2040, the projected increase in global mean surface temperature is approximately **1.5–1.6 °C**, depending on the SSP scenario. For 2041–2060, the differences among the scenarios become more pronounced, ranging from approximately **1.6 °C under SSP1-1.9** to **2.4 °C under SSP5-8.5**, relative to the 1850–1900 reference period.

Accordingly, the temperature curve presented for the **2025–2050 planning period** is derived by interpolation from the IPCC AR6 projections. It therefore represents an **analytically derived illustrative temperature trajectory**, rather than original annual temperature values reported directly in the IPCC tables [1].

For Bosnia and Herzegovina (BiH), the intermediate **SSP2-4.5** pathway can be used as a suitable baseline or moderate scenario for planning purposes. However, climate-risk assessments should also consider the high-emissions **SSP5-8.5** scenario in parallel. This is particularly important when analysing flood risk, prolonged drought conditions, extreme precipitation, and the hydraulic capacity and design of urban sewer systems.

The parallel consideration of SSP2-4.5 and SSP5-8.5 therefore provides a useful scenario range for assessing the potential impacts of climate change on urban wastewater systems in BiH during the 2025–2050 planning period.

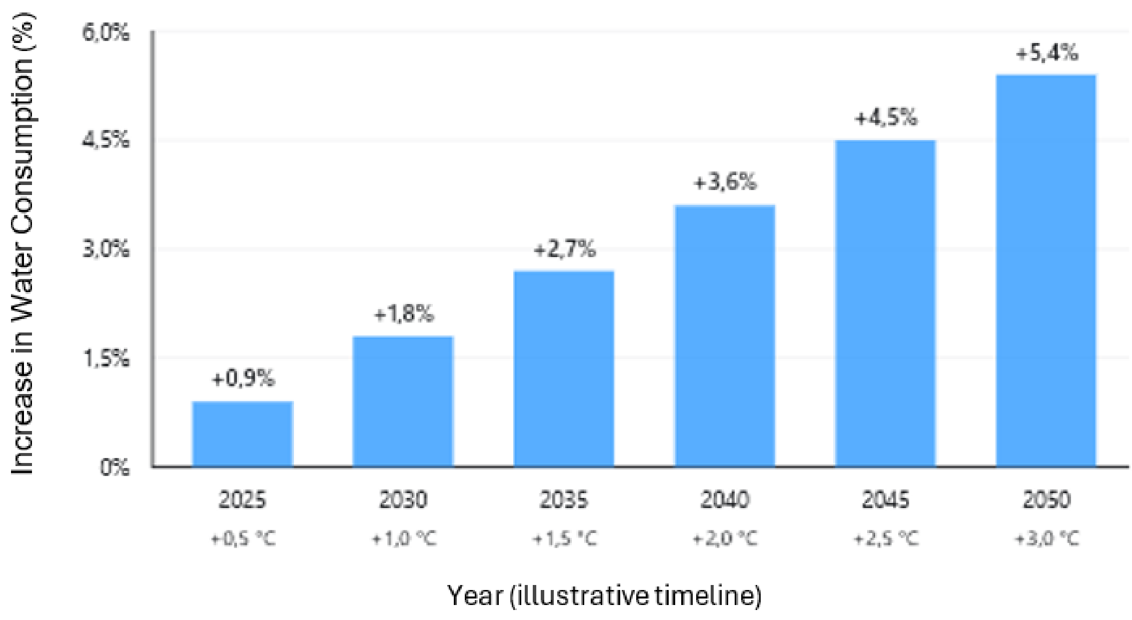

Figure 3.2. Increase in Mean Temperature and Specific Water Consumption

Figure 3.2 presents an illustrative temporal trajectory up to 2050, showing the potential relationship between increasing air temperature and specific water consumption. An increase in temperature ranging from +0.5 to +3.0 °C is assumed to result in an increase in specific water consumption of approximately 0.9–5.4%, based on an assumed increase of 1.8% per 1 °C and an initial specific water consumption of 150 L/capita/day.

According to these assumptions, specific water consumption would increase from the baseline value of 150 L/capita/day to approximately 151.4 L/capita/day at a temperature increase of +0.5 °C and to approximately 158.1 L/capita/day at +3.0 °C.

These values should be interpreted as an illustrative modelling relationship rather than observed or directly projected values. The actual response of water consumption to increasing temperature depends on local conditions and may vary considerably among urban areas. Relevant factors include the duration and intensity of droughts and heat waves, water pricing, water-use restrictions, household behaviour, tourism, socioeconomic conditions, and the characteristics of the local water-supply system [7,8].

For the wastewater model, this relationship provides a simplified means of representing the potential indirect effect of increasing air temperature on **water demand and, consequently, municipal wastewater generation** during the 2025–2050 planning period.

For the illustrative model, a temperature sensitivity coefficient of 1.8% $°C^{-1}$ was assumed. This coefficient represents a modelling assumption used to demonstrate the potential effect of increasing air temperature on specific urban water consumption, while the direction and magnitude of the relationship are supported by previous studies [20,21,22].

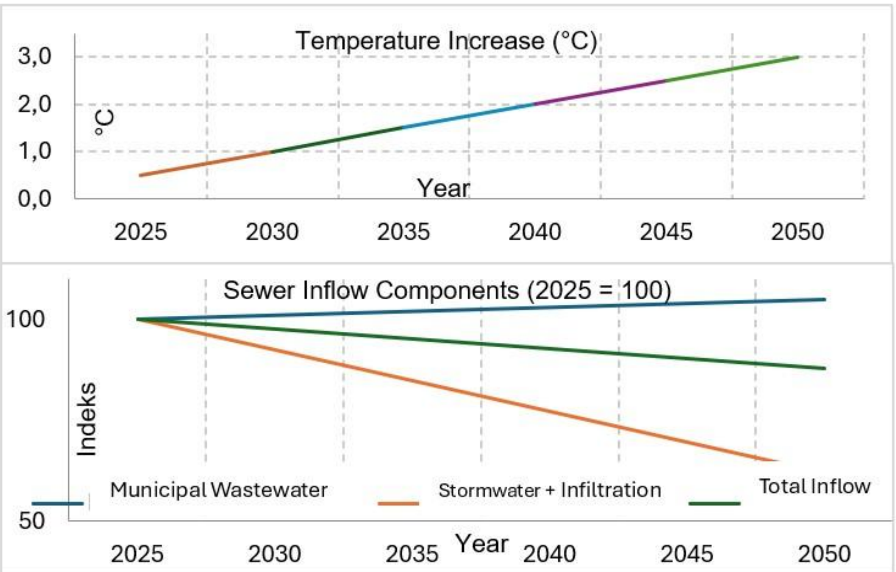

Figure 3.3. Effect of Increasing Air Temperature on Urban Wastewater Quantity

The following graph distinguishes between two climate-related effects. Higher air temperatures may cause a moderate increase in municipal water consumption and, consequently, municipal wastewater generation, whereas prolonged drought conditions may have a stronger reducing effect on stormwater and infiltration entering the sewer system. As a result, the total inflow to a combined sewer system may decrease during prolonged hot and dry periods, while wastewater pollutant concentrations may increase due to reduced dilution.

Figure 3.3 presents an illustrative temporal trajectory of air temperature, municipal wastewater, stormwater and infiltration, and total sewer inflow for the planning period 2025–2050. To enable comparison of variables with different physical units, all values are expressed as indices relative to the reference year 2025 = 100.

The figure therefore illustrates the combined effects of increasing temperature and changing hydrological conditions on the quantity and composition of wastewater conveyed through a combined sewer system. The presented trends should be interpreted as model-based illustrative trajectories rather than directly observed values. Their primary purpose is to support the analysis of potential climate-change impacts and subsequent simulation of urban wastewater system performance [9,10,11].

For the analysis of wastewater quality, **five-day biochemical oxygen demand (BOD_5)** was selected as the principal indicator for assessing changes in the concentration and organic pollution load of wastewater in urban areas. BOD_5 is widely used as an indicator of biodegradable organic pollution and therefore provides an appropriate parameter for illustrating potential changes in wastewater quality under different climatic conditions.

The analysis distinguishes between the effects of **drought and extreme rainfall events**. During prolonged hot and dry periods, reduced stormwater and infiltration inflows decrease wastewater dilution and may consequently increase BOD_5 concentrations in the sewer system. In contrast, extreme rainfall events may temporarily reduce BOD_5 concentrations through dilution while simultaneously increasing hydraulic flow, total pollutant transport, the risk of hydraulic overloading, and the occurrence of **combined sewer overflows (CSOs)**.

Higher wastewater and receiving-water temperatures may additionally affect biochemical and microbiological processes and reduce dissolved oxygen availability in receiving waters. Therefore, the combined effects of temperature, drought, and extreme precipitation should be considered when assessing climate-related changes in wastewater quality [12].

The temperature range applied in the analysis is consistent with the climate projections for **Bosnia and Herzegovina presented in the National Adaptation Plan (NAP)**. The resulting BOD_5 values should be interpreted as **model-based illustrative estimates**, rather than directly observed concentrations, and are used to demonstrate potential trends in wastewater quality under changing climatic conditions [2,5].

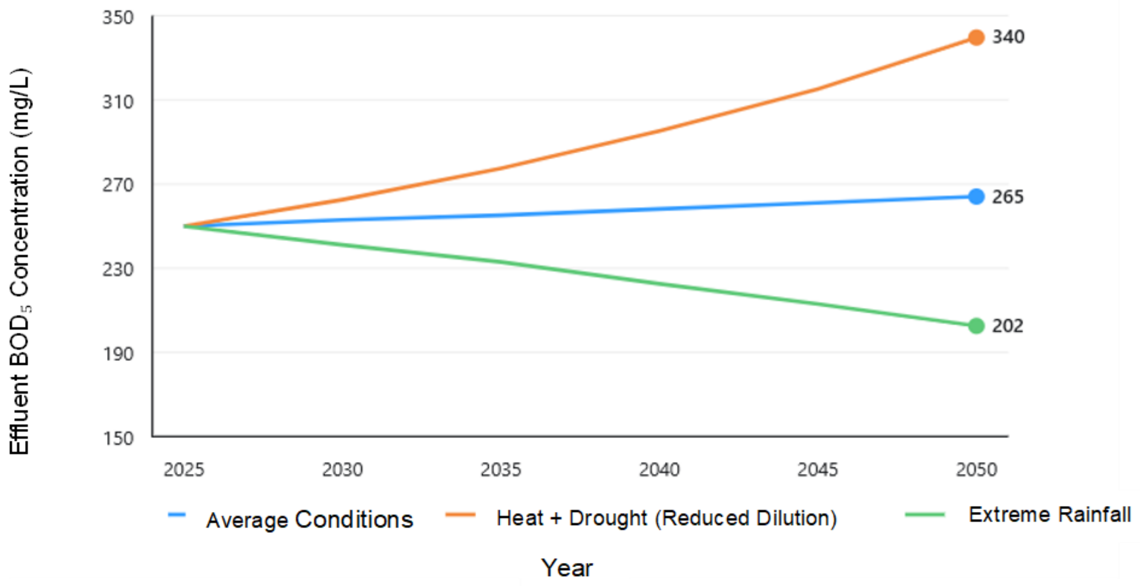

Figure 3.4. Increase in BOD_5 Concentration (mg/L) Due to Rising Temperature, Prolonged Drought, and Extreme Rainfall Events

In general, the current condition and characteristics of urban wastewater in Bosnia and Herzegovina (BiH) remain insufficiently investigated and addressed. Sewerage coverage and wastewater treatment capacities are unevenly developed, while a proportion of wastewater is still discharged into receiving water bodies without adequate treatment. Such conditions pose risks to the quality of rivers, groundwater resources, aquatic ecosystems, and water sources used for public water supply [23,24,25].

Climate change further increases these risks (Figure 3.5). More intense short-duration precipitation events may hydraulically overload combined sewer systems and lead to the discharge of untreated or partially treated wastewater through sewer overflows. In contrast, prolonged drought periods reduce stormwater and infiltration inflows and consequently decrease dilution within sewer networks. These conditions may result in higher concentrations of organic pollutants, including BOD_5, as well as increased problems associated with sediment deposition, odour generation, reduced flow velocities, and the operation of wastewater treatment plants.

Therefore, the key priorities for Bosnia and Herzegovina include expanding and rehabilitating sewer networks and wastewater treatment infrastructure, separating stormwater from sanitary wastewater where technically and economically feasible, establishing systematic monitoring of wastewater flows and BOD_5 concentrations, and incorporating climate-change scenarios into the planning, design, and management of wastewater infrastructure.

The National Adaptation Plan (NAP) of Bosnia and Herzegovina provides an important framework for such an approach, highlighting increasing temperatures and climate-related risks to the water sector. Accordingly, future wastewater management in BiH should integrate both existing infrastructure deficiencies and projected climate-related changes in hydrological conditions. This integrated approach is essential for increasing the resilience, reliability, and long-term sustainability of urban wastewater systems under future climate conditions.

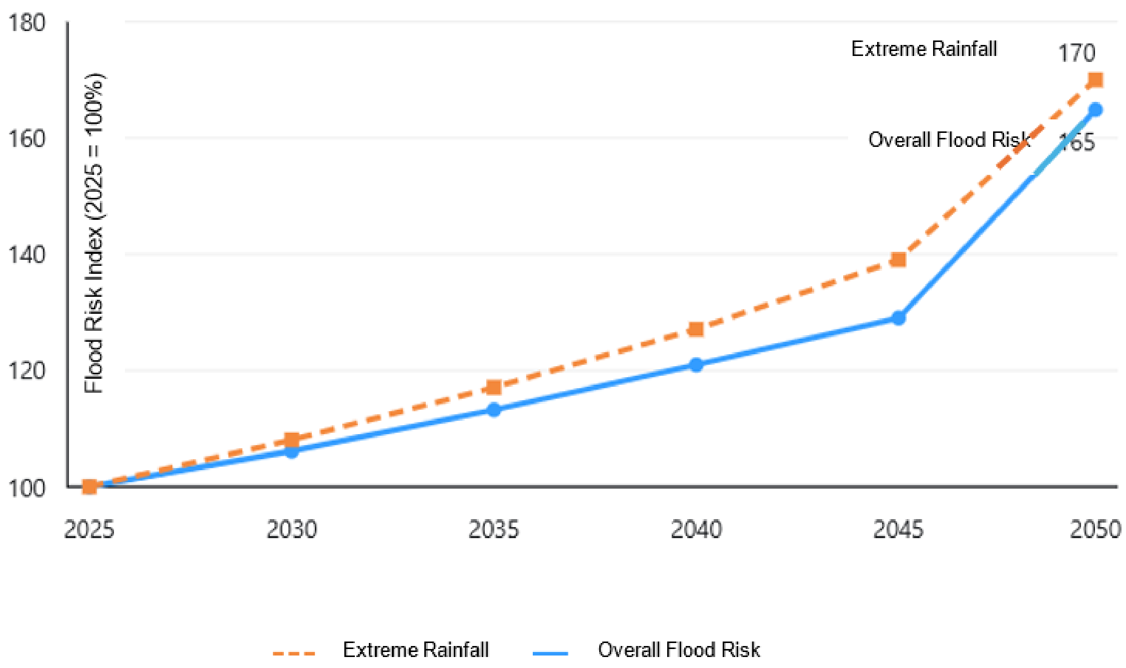

Figure 3.5. Increasing Risk to Urban Wastewater Systems Due to Extreme Climate Events

4. IMPACT OF CLIMATE CHANGE ON WASTEWATER CONDITIONS IN THE CITY OF MOSTAR: APPLICATION OF THE URBAN WATER SYSTEM MANAGEMENT MODEL (MODEL_MO_UVS)

Based on the previous analysis of the major impacts of climate change on wastewater conditions and the projected trends over the selected planning period, a simulation was performed to assess the operation of the wastewater drainage system and potential changes in the **quantity and quality of wastewater in the City of Mostar**. The simulation was carried out using the previously developed **urban water system management model (MODEL_MO_UVS)** [18,19].

The model was developed as an example of the application of an appropriate methodology and modelling tools for the analysis, simulation, and management of complex urban water systems. It is based on **Object-Oriented Modelling (OOM)** and was developed using the **STELLA** system dynamics modelling software [14,16].

The developed and applied model integrates the principal physical and management components of the urban water system. These include a **water quantity model**, a **water quality model for the wastewater drainage system**, and an **economic model for the management of the overall urban water system**. This integrated modelling structure enables interactions among the major system components to be represented and provides a basis for analysing changes in system behaviour under different operating and climatic conditions.

For the illustrative simulation and presentation of system behaviour in this study, only the climate-change components considered most relevant to the wastewater system were selected. These include:

- **increasing air temperature**;
- **prolonged drought periods**; and
- **more intense extreme precipitation events**.

These climate drivers were incorporated into the model as external influencing factors affecting wastewater generation, stormwater and infiltration inflows, total sewer-system inflow, wastewater pollutant concentrations and loads, and consequently the overall performance of the urban wastewater system [13].

The modelling approach therefore enables the potential effects of different climate conditions to be analysed within a common system framework and provides a basis for identifying the components and parameters most sensitive to climate change. The results are intended primarily to illustrate potential trends and interactions within the Mostar urban wastewater system rather than to represent deterministic predictions of future conditions.

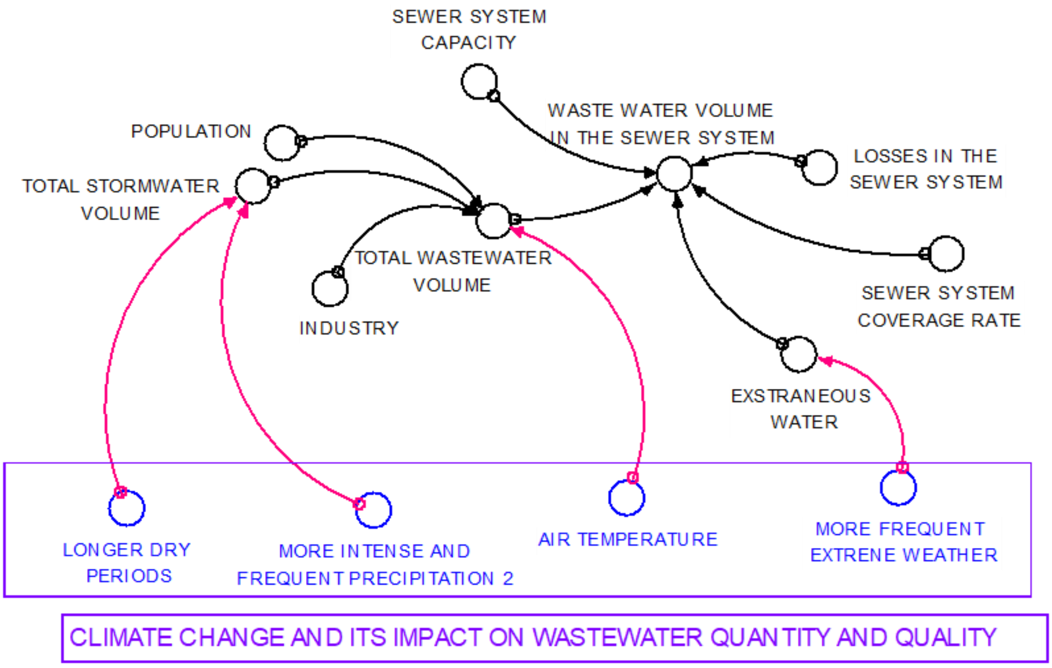

Figure 4.1. Schematic Representation of the Main Components Affecting the Wastewater Quantity Balance in the Sewer System

From the developed model, the key components contributing to the **total wastewater quantity in the sewer system** were identified (Figure 4.1.) geher with the components that directly influence **wastewater quality** (Figure 4.2.).

For a longer time period (**T**), the wastewater quantity balance in the sewer system can be expressed as:

$$(V_{OV,k})_T = \sum_{t=1}^{T} Q_{t,OV,K} \cdot \Delta t \ \ (m^3) \quad \text{............................ (4.1)}$$

Tat is to say:

$$V_{tot}(T) = V_{mw}(T) + V_{ind}(T) + V_{sw}(T) + V_{inf}(T) - V_{loss}(T) - V_{CSO}(T) \text{........................ (4.2)}$$

where:

Variable	Definition
V_{tot}	total wastewater volume conveyed through the sewer system during period T;
V_{mw}	municipal wastewater volume;
V_{ind}	industrial wastewater volume;
V_{sw}	stormwater volume entering the sewer system;
V_{inf}	infiltration/inflow volume;
V_{loss}	losses from the sewer system; and
V_{CSO}	wastewater volume discharged through combined sewer overflows (CSOs).

Accordingly, Figure 4.1 presents a graphical scheme of the components contributing to the total wastewater quantity generated and conveyed through the sewer system, as represented in the STELLA modelling environment. Based on this conceptual representation, the total wastewater quantity balance was formulated and expressed mathematically in Equations (4.1) and (4.2).

A similar approach can be applied to assess the impact of climate change on wastewater quality, focusing on five-day biochemical oxygen demand (BOD_5) as one of the key indicators of organic pollution. For this purpose, the average BOD_5 concentration (mg/L) in urban wastewater was adopted as the representative water-quality parameter.

Based on the wastewater quantity balance defined by Equations (4.1) and (4.2), the total BOD_5 pollutant load, and the previously described characteristics of the individual components of the sewer system, the overall BOD_5 concentration within the sewer system during the wastewater conveyance process can be determined.

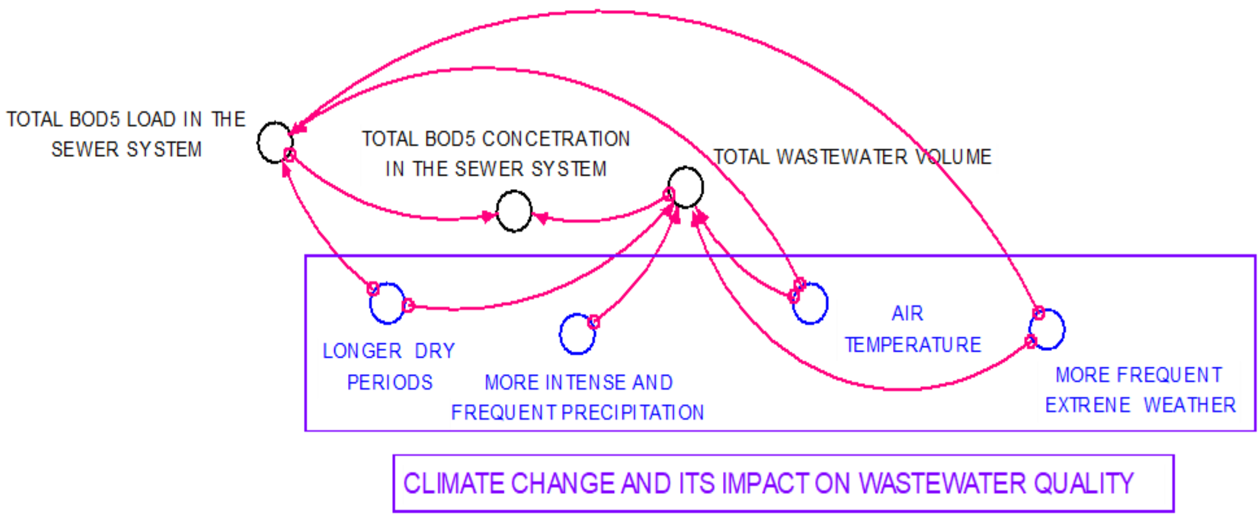

Figure 4.2. Schematic Representation of the Main Components Affecting BOD_5 Concentration and Pollutant Load in the Sewer System

The relationships among the individual wastewater components, their respective BOD_5 concentrations and pollutant loads, and the resulting total BOD_5 concentration can also be represented graphically. The corresponding conceptual structure implemented in the STELLA modelling environment is presented in Figure 4.2.

The **City of Mostar**, more specifically its urban area, was selected as a case study for the application of the developed model. The case study is used primarily to demonstrate the applicability of the proposed model and methodology for the **sustainable management of**

urban water systems (UWSs), particularly through simulation and optimisation of system operation.

It should be emphasised that the application of the model and the proposed methodology to the urban water system of Mostar is **not intended to provide a comprehensive solution to all existing water-management problems of the City of Mostar**. Rather, the Mostar UWS serves as a representative case study for testing and demonstrating the proposed methodology and model. The analysis of the simulation and optimisation results makes it possible to demonstrate the approach, applicability, and potential advantages of the proposed methodology for addressing sustainable urban water management problems in cities in general, particularly under **changing climatic conditions**.

In other words, the selected case study is intended to:

1. **Apply the developed model and proposed methodology to a specific urban water system**, thereby reproducing the behaviour of a real system under two principal sets of conditions: a baseline condition without explicitly considering climate-change impacts and a climate-change condition incorporating the major relevant climate-related drivers.
2. **Analyse the characteristics and applicability of the model and methodology** for managing the UWS of the selected case study, including a comprehensive analysis of the results obtained through the simulation and optimisation procedures.
3. **Assess the usefulness and applicability of the model and methodology for the optimal and sustainable management of urban water systems.**

Based on the above, two primary objectives can be defined for the application of the model to the urban water system of the City of Mostar.

First objective: To demonstrate that the developed model can be used for managing and analysing an urban water system by assessing its existing condition and simulating its potential future behaviour under the influence of significant climate-change drivers over the selected **2025–2050 planning period**.

Second objective: To demonstrate and assess how the developed model and proposed methodology can be used to improve system performance and support the **optimal management and sustainable development of the urban water system**.

Accordingly, the Mostar case study provides a framework for comparing the behaviour of the UWS under **baseline and climate-change scenarios**, identifying climate-sensitive system components, evaluating potential changes in system performance, and assessing possible management and adaptation measures. The case study therefore serves primarily as a **methodological demonstration and model-validation framework**, rather than as a definitive engineering solution for the urban water system of Mostar.

4.1. Output Results (Graphs) and Discussion of the Results

The total wastewater quantity (sanitary wastewater and stormwater) conveyed through the sewer system during the 2025–2050 planning period shows a slight increasing trend under baseline conditions. This increase is primarily associated with the projected increase in specific water consumption, urbanisation, and other parameters affecting municipal wastewater generation.

However, when the relevant climate-change-related factors are incorporated into the model, as presented in the schematic representation in Figure 4.1, the simulation indicates a reduction in the total wastewater quantity conveyed through the sewer system compared with the baseline scenario.

This reduction can primarily be attributed to the combined effects of higher air temperatures, prolonged drought periods, changes in precipitation patterns, and reduced stormwater and infiltration/inflow contributions to the sewer system. Although higher temperatures may moderately increase specific water consumption and consequently sanitary wastewater generation, this effect may be outweighed by the reduction in stormwater and infiltration/inflow during prolonged dry periods.

Therefore, the simulation results indicate two different trends: a baseline scenario, characterised by a gradual increase in total wastewater quantity, and a climate-change scenario, in which climate-related changes in the water balance result in a lower total sewer inflow. The simulated trends for the 2025–2050 period are presented in Figure 4.3.

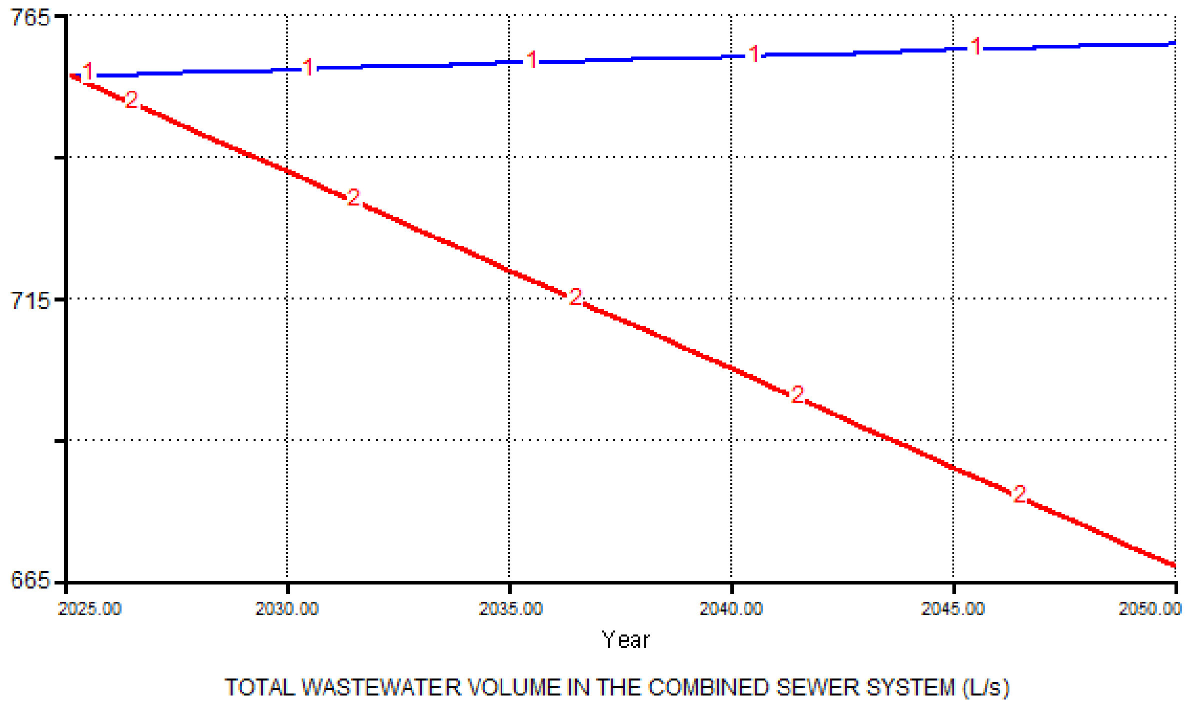

Figure 4.3. Wastewater Quantity Trends in the Sewer System during the 2025–2050 Planning Period

1 – Curve showing a slight increase in total wastewater quantity during the planning period **without the effects of climate change (baseline scenario)**.

2 – Curve showing a decreasing trend in total wastewater quantity **under the influence of the main climate-change-related factors (climate-change scenario)**.

The graph presents the simulated wastewater flow conditions for the City of Mostar over the selected planning period. At the beginning of the simulation period, the total wastewater flow is **Q = 754 L/s**. Under the scenario **without climate-change impacts (baseline scenario)**, the model indicates a slight increase in wastewater flow, reaching approximately **Q = 760 L/s by 2050**.

When the relevant climate-change effects are incorporated into the model for the same planning period, the simulated average wastewater flow decreases to approximately **Q = 667 L/s by 2050**. Compared with the baseline value of 760 L/s, this corresponds to a reduction of approximately **12.2%**.

The simulation therefore indicates that the combined effects of **increasing temperature, prolonged drought periods, reduced stormwater and infiltration/inflow, and other climate-related factors** may lead to a decrease in the **average total wastewater flow** conveyed through the sewer system. However, this reduction in average flow does not imply a reduction in the required hydraulic capacity of the sewer system.

On the contrary, climate change may simultaneously increase the magnitude and frequency of **short-duration extreme flows associated with intense precipitation events**. Such peak flows are particularly important for assessing the hydraulic performance, design capacity, and risk of overloading of sewer collectors, pumping stations, combined sewer overflows, and wastewater treatment facilities. Therefore, both the **long-term trend in average wastewater flow** and the occurrence of **short-duration extreme flow events** should be considered when planning and optimising the future sewer system.

The simulated changes in **wastewater quality** are presented in the following graph (**Figure 4.4**).

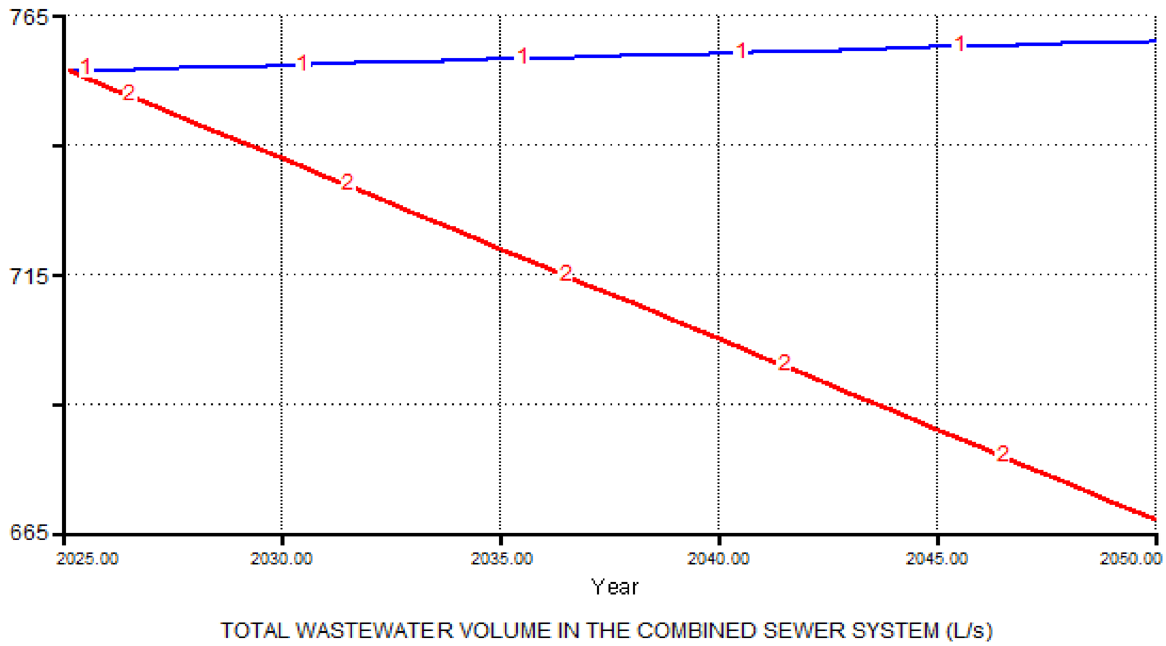

Figure 4.4. Comparison of BOD_5 Concentration Trends in the Sewer System with and without Climate-Change Effects during the 2025–2050 Planning Period

1 – Curve representing the BOD_5 concentration in wastewater during the planning period **without the effects of climate change (baseline scenario)**.

2 – Curve representing the increase in BOD_5 concentration in wastewater **under the influence of the main climate-change-related factors (climate-change scenario)**.

The graph presents the simulated **BOD_5 concentration (mg/L)**, which was selected as a key indicator of the organic pollution level and overall wastewater quality. At the beginning of the planning period, the BOD_5 concentration for the City of Mostar is **Kc = 291 mg/L**. Under the scenario **without climate-change impacts (baseline scenario)**, the concentration remains relatively stable, reaching approximately **Kc = 293 mg/L by 2050**.

When the relevant climate-change effects are incorporated into the model, the simulation indicates a substantial increase in BOD_5 concentration over the planning period, reaching approximately **Kc = 408 mg/L by 2050**. Compared with the baseline scenario value of 293 mg/L in 2050, this represents an increase of approximately **39.2%**.

The results therefore indicate that the combined effects of the major climate-change drivers defined in the previous sections, together with the simulated reduction in total wastewater flow and consequently reduced dilution within the sewer system, may significantly affect wastewater quality. In particular, **increasing air temperature, prolonged drought periods, reduced stormwater and infiltration/inflow, and changes in hydrological conditions** contribute to conditions under which higher BOD_5 concentrations may occur.

Thus, although the model indicates a reduction in the **average wastewater quantity** under climate-change conditions, it simultaneously indicates a deterioration in wastewater quality in terms of increased **BOD_5 concentration**. This result highlights the importance of considering wastewater **quantity and quality simultaneously** when assessing the effects of climate change on urban wastewater systems.

It should also be emphasised that an increase in BOD_5 concentration does not necessarily imply an equivalent proportional increase in the **total BOD_5 pollutant load**, since the pollutant load depends on both concentration and wastewater flow. Therefore, the assessment of climate-change impacts should consider both **BOD_5 concentration (mg/L)** and **BOD_5 load (kg/day)**.

The analysis of the key parameters describing the impacts of climate change on urban wastewater systems led to the following conclusions:

- **More intense and frequent precipitation events** represent one of the most important climate-change-related challenges for urban water management. They increase the risk of urban flooding, hydraulic overloading of sewer systems and wastewater treatment plants, deterioration of surface-water quality, and damage to municipal infrastructure. Therefore, adaptation of urban areas to changing climatic conditions through the modernisation of drainage systems and implementation of sustainable solutions is essential for reducing risks and increasing urban resilience.
- **Prolonged drought periods** represent a serious challenge for urban water management in Bosnia and Herzegovina. They reduce the availability of water resources, may increase water demand, deteriorate surface-water quality, and

adversely affect the operation of sewer systems and wastewater treatment plants. Under projected future climate conditions, adaptation of water infrastructure, efficient water-resource management, and implementation of sustainable measures are essential for ensuring reliable water supply and protecting the urban environment.

- **Increasing air and water temperatures** are among the principal drivers of changes in the urban water cycle. Higher temperatures increase evaporation and evapotranspiration, reduce the availability of water resources, affect surface-water quality, promote algal growth, and contribute to lower dissolved oxygen concentrations. Consequently, cities need to develop more resilient water-supply and water-management systems capable of operating effectively under increasingly pronounced climate-related pressures.
- **Extreme weather events**, including intense precipitation, floods, droughts, and heat waves, increase pressure on urban water infrastructure, adversely affect water quality, and may result in substantial economic and social damage. Considering the expected continuation of climate change, existing systems need to be adapted to changing climatic conditions, urban resilience needs to be strengthened, and an integrated approach to urban water and natural-hazard risk management should be adopted.
- **Climate change may significantly alter urban wastewater quality** through changes in temperature, precipitation regimes, drought duration, and the frequency of extreme weather events. Intense rainfall can cause wastewater dilution while simultaneously producing substantial hydraulic overloading of sewer networks and treatment facilities. In contrast, prolonged drought conditions reduce dilution and may increase pollutant concentrations. Higher temperatures accelerate biological and chemical processes, increase the risk of corrosion and odour generation, and may affect wastewater treatment efficiency. Adaptation of sewer networks and wastewater treatment plants is therefore essential for protecting receiving-water quality and public health under changing climatic conditions.

The analysis and simulation results obtained for the **urban water system (UWS) of the City of Mostar** indicate that climate-related changes may require modifications in both system operation and management. The modelling approach enables the identification, in both temporal and functional terms, of critical system components where interventions may be required to improve performance and resilience.

The simulation results demonstrate an important interaction between **wastewater quantity and quality**. Under the baseline scenario, the total wastewater flow increases slightly from approximately **754 L/s in 2025 to 760 L/s in 2050**. When the selected climate-change effects are incorporated into the model, the simulated average flow decreases to approximately **667 L/s in 2050**, corresponding to a reduction of approximately **12.2% compared with the 2050 baseline scenario**. At the same time, extreme precipitation events may generate substantially higher short-duration peak flows, which remain critical for the hydraulic capacity and design of the sewer system.

The wastewater-quality simulation indicates the opposite tendency. The selected indicator, **BOD_5 concentration**, changes only slightly under baseline conditions, from approximately **291 mg/L in 2025 to 293 mg/L in 2050**. Under the climate-change scenario, however, the simulated BOD_5 concentration reaches approximately **408 mg/L by 2050**, representing an increase of approximately **39.2% compared with the 2050 baseline value**. These results illustrate that a reduction in average wastewater flow, particularly as a consequence of prolonged dry periods and reduced dilution, may be accompanied by a substantial increase in pollutant concentration.

Consequently, the effects of climate change on wastewater systems should not be evaluated exclusively through changes in average flow. **Average wastewater quantity, short-duration peak flows, pollutant concentrations, pollutant loads, treatment performance, and receiving-water conditions should be considered simultaneously.** In particular, an increase in BOD_5 concentration does not necessarily correspond to an equivalent increase in BOD_5 pollutant load, since the latter depends on both wastewater concentration and flow.

The application of **Object-Oriented Modelling (OOM) within the STELLA system dynamics modelling environment** demonstrates one possible approach for analysing and improving UWS performance. The methodology is based on systems analysis, identification of interactions among system components, and sensitivity analysis of selected parameters. Through **“what-if” scenario analysis**, the model can be used to investigate potential future system behaviour under continuation of current trends and to compare it with system behaviour under selected climate-change conditions.

The simulation results and corresponding graphical outputs demonstrate how such a model can support the identification of critical system components and provide a basis for evaluating potential optimisation and adaptation measures. The model should therefore be considered primarily as a **decision-support and scenario-analysis tool**, rather than as a deterministic prediction of future conditions.

Based on the analysis, the principal adaptation and management measures can be summarised as follows:

- To reduce the consequences of **intense precipitation and urban flooding**, measures should include increasing sewer-system capacity where justified, separating stormwater and sanitary wastewater where technically and economically feasible, constructing retention and detention facilities, implementing sustainable urban drainage systems (SuDS), increasing green and permeable urban surfaces, and introducing rainfall monitoring and flood early-warning systems.
- To mitigate the effects of **prolonged droughts**, priority measures include reducing losses in water-supply networks, using alternative water sources such as rainwater harvesting and treated wastewater reuse where appropriate, implementing digital monitoring and real-time water-system management, regularly flushing sewer networks to prevent sediment accumulation, increasing water-storage capacity, and promoting efficient water use.
- To mitigate the adverse effects of **increasing temperatures**, measures should include protection of water sources and receiving water bodies, expansion of urban green infrastructure to reduce the urban heat-island effect, rational water-demand management, continuous monitoring of water temperature and quality, and implementation of appropriate advanced drinking-water and wastewater treatment technologies.
- To reduce climate-related impacts on **wastewater quality**, measures should include upgrading wastewater treatment plants, separating stormwater and sanitary wastewater where feasible, applying advanced treatment technologies where required—including membrane processes, ozonation, activated-carbon adsorption, and advanced oxidation processes—continuous wastewater-quality monitoring using digital sensors, improving treatment-plant energy efficiency, and developing treated wastewater reuse systems, particularly for irrigation and appropriate industrial applications.

Overall, the presented approach represents an **illustrative and potentially effective methodology for assessing system behaviour and parameter sensitivity under climate-change conditions**. The selected parameters enable the principal interactions between climate drivers, wastewater quantity, and wastewater quality to be incorporated into a common modelling framework.

The Mostar case study supports the applicability of **Object-Oriented Modelling combined with systems analysis and scenario simulation** for the functional, sustainable, and potentially optimal management of urban wastewater systems. More broadly, the methodology provides a framework that can be adapted to other urban areas, provided that the model is calibrated and validated using appropriate local hydrological, hydraulic, wastewater-quality, infrastructure, and climate data.

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