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An Assessment of Water Management at a Major Global Hub Airport: A Case Study of Frankfurt Airport

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Abstract**—***Increasingly, airports have increased their focus on sustainable water management. Airports consume large quantities of water to maintain their infrastructure and to facilitate both air and ground-based operations. Airports are also the source of runoff or waste waters, which can be very substantial in nature. Using an in-depth qualitative longitudinal research design, this study has examined Frankfurt Airport, a major global hub airport, sustainable airport water management practices. The qualitative data was examined by document analysis. The study period was from 2008 to 2019. The case study found that Frankfurt Airport's annual water consumption, water consumption per workload unit (WLU), and water consumption per aircraft movement largely exhibited an upward trend over the study period. This growth was influenced by strong growth in passenger traffic and aircraft movements recorded during the study period. The annual consumption of drinking water and the annual sewage waters fluctuated over the study period. There was an overall general upward trend in the sewage waters per workload unit (WLU). Frankfurt Airport has installed extensive water management infrastructure. Frankfurt Airport operates its own sewage treatment plant. Wastewaters generated at the airport is treated in Frankfurt Airport's fully biological water treatment together with the fully biological water treatment plants in Frankfurt Niederrad and Frankfurt Sindlingen. Frankfurrt Airport also operates several rainwater treatment plants. The airport also has grease and oil separators and demulsification plants. The case study found that Frankfurt Airport is making greater use of rainwater, treated water from the River Main, as well as well water.*

Keywords**— *Airport water management; Case study; Drinking water; Frankfurt Airport; Service waters, Sewage waters, Water consumption***

I. INTRODUCTION

The transportation of passengers and air cargo consignment by airlines occurs within the air transport value chain (Jarach, 2017). The air transport value chain is comprised of key actors, which includes airlines, airports, aircraft maintenance organizations, ground handling agents, and flight catering centres. Airports play a pivotal role in the air transport value chain by facilitating the movement of passengers and air cargo between the air and surface-based transport modes. Underpinning an airport's ability to meet its key stakeholder demands is the provision of terminal buildings, systems, and airfield infrastructure, for example, runways and taxiways. Airports are resource intensive, particularly so for energy and water consumption. Water consumption at airports is very substantial, as airports and their key stakeholders require large amounts of water to maintain their infrastructure and their operational activities (de Castro Carvalho et al., 2013). Airports are also source of run-off waters (Baxter et al., 2018; Sulej et al., 2011; Sulej-Suchomska et al., 2016). McGormley (2011, p. 83) has noted that "airport operations routinely interact with water resources from the treatment and distribution of drinking water to the discharge of stormwater into surrounding rivers, streams or lakes". Considering the impact that the high-water consumption and the runoff waters have on the environment, airports are increasingly focusing on sustainable water management (Somerville et al, 2015). Sustainable water management is now a key element in airport's environmental and sustainability policies and practices (Baxter, 2021a).

The objective of this study is to empirically examine how a major global hub airport sustainably manages its water consumption as well as the processes for managing its sewage and wastewaters. Frankfurt Airport, Germany's largest airport, and a major global hub airport, was selected as the case airport due to its long held sustainable water management practices. A second objective of the study was to examine how the increases in air traffic and aircraft movements at the airport recorded throughout the study period have influenced water consumption at Frankfurt Airport. A final objective was to examine the sustainable water management practices that have been implemented by the airport. Frankfurt Airport was selected as the case airport as it is a major global hub airport that is served by both full-service network carriers (FSNCs), low-cost carriers (LCCs), regional airlines, and dedicated air cargo carrying airlines. The availability of a comprehensive data set covering the period 2008 to 2019, was a further factor in selecting Frankfurt Airport as the case airport.

The remainder of the paper is organized as follows: The literature review that sets the context of the case study is presented in Section 2. The research method that underpinned the case study is presented in Section 3. The case study is presented in Section 4. Section 5 presents the findings of the study.

II. BACKGROUND

2.1 Airport Stakeholders Water Requirements and Usage

As previously noted, airports consume substantial volumes of water to maintain both their infrastructure, and thus, sustain their aircraft and ground-based operations (Baxter et al., 2018; de Castro Carvalho et al., 2013, Neto et al., 2012). Airport operators, airlines, air traffic management agencies, ground handling agents, aircraft and ground service equipment (GSE) maintenance organizations, airport concessionaires, and passengers and staff require water for drinking, catering, retail, cleaning, flushing toilets, and system maintenance. Water is also used to maintain an airport grounds and during the landscaping of gardens and parks that are located within the airport precinct (Thomas & Hooper, 2013).

2.2 Airport Runoff Waters

In an airport's operational area, run-off waters pose a significant environmental threat. These waters could have a negative impact on both soil and groundwater since they contain a relatively high concentration of contaminants (Vanker et al., 2013). Wastes associated with aircraft refueling, aircraft operations, aircraft and ground service equipment (GSE) maintenance and equipment and facilities cleaning can potentially enter lakes and streams located nearby to the airport via the airport's storm water drainage system. Major aircraft overhauls that use toxic chemicals to remove paint pose an environmental threat should these toxic chemicals enter the water system (Culberson, 2011). Other contaminants originating from operations or activities undertaken at an airport include detergent formulations, solids, oils, greases, residues, solvent residues, and heavy metals (Grantham, 1996). The discharge of fire-fighting foam during an aircraft emergency (Fawell, 2014) together with the production of in-flight meals, and meals served at restaurants and staff canteens also contribute grease and detergents to the wastewater generated at an airport (Baxter et al., 2019).

2.3 Airport Water Processing Plants

Rainwater from the paved areas, particularly from the airport's apron areas, can be cleaned using a special treatment plant located at the airport. This facility will separate oil products from the waters. Alternatively, a collector can be connected to the local municipal treatment plant. Fuel storage, and aircraft hangars and aircraft and ground service equipment (GSE) maintenance facilities, should be equipped with traps to catch any waste oil products. These facilities should be inspected regularly (Kazda et al., 2015).

2.4 Airport Water Conservation Measures

Because of the increasing pressure to reduce water consumption and conserve available water resources, airports can implement a range of measures that will enable them to reduce their water consumption. To achieve their environmental-related and sustainability goals, many airports around the world have implemented a range of water-related initiatives (Dimitriou & Voskaki, 2011). These water conservation measures include the overall reduction in water consumption at the airport (Baxter et al., 2019; Rossi & Cancelliere, 2013), re-using water from the treatment of waters at wastewater and sewage treatment plants in toilet facilities and for irrigation purposes (Baxter et al., 2018, 2019; Chen et al., 2012), using rainwater for the flushing of the toilets in airport buildings and facilities (Baxter et al., 2018, 2019; Yu et al., 2013), protecting groundwater from pollution (Gupta & Onta, 1997), the overall monitoring of water consumption at the airport (Boyle et al., 2013), and monitoring the surface and ground water quality (Bartram & Balance, 1996; Baxter et al., 2019; Thomas & Hooper, 2013). Airports also need to protect surface and ground water resources (Thomas & Hooper, 2013).

III. RESEARCH METHODOLOGY

3.1 Research Method

The study's qualitative analysis was underpinned by a longitudinal case study research design (Derrington, 2019; Hassett & Paavilainen-Mäntymäki, 2013; Neale, 2019). The primary advantage of a qualitative longitudinal research design is that it reveals change and growth in an outcome over time (Kalaian & Kasim, 2008). A case study allows for the in-depth examination of complex phenomena (Cua & Garrett, 2009; Remenyi et al., 2010; Yin 2018) and enables the collection of rich, explanatory information (Ang, 2014; Mentzer & Flint, 1997). A further advantage of case studies is that they enable researchers to build theory and connect with practice (McCutchen & Meredith, 1993).

3.2 Data Collection

The qualitative data was sourced from Fraport AG's annual environmental statements. Thus, in this study secondary data was used to investigate the research objectives. The three guiding principles of data collection in case study research as suggested by Yin (2018) were followed in this study: the use of multiple sources of case evidence, creation of a database on the subject, and the establishment of a chain of evidence.

3.3 Data Analysis

The data collected for the case studies was examined using document analysis. Document analysis is often used in case studies and focuses on the information and data from formal documents and company records (Ramon Gil-Garcia, 2012). Existing documents provide a vital source of qualitative data (Woods & Graber, 2017). Furthermore, documents are one of the principal forms of data sources for the interpretation and analysis in case study research (Olson, 2010). The documents collected for the present study were examined according to four criteria: authenticity, credibility, representativeness, and meaning (Fitzgerald, 2012; Scott, 2004, 2014).

The key words used in the database searches included "Fraport AG environmental management policy", "Frankfurt Airport's total annual water consumption", "Frankfurt Airport's total annual water consumption per traffic unit", "Frankfurt Airport's total annual drinking water consumption", "Frankfurt Airport's total annual service water consumption", and "Frankfurt Airport's total annual sewage waters", "Frankfurt Airport's total annual sewage waters per traffic unit".

The study's document analysis was conducted in six distinct phases. The first phase involved planning the types and required documentation and ascertaining their availability for the study. In the second phase, the data collection involved sourcing the documents from Fraport AG and developing and implementing a scheme for managing the gathered documents. The collected documents were examined to assess their authenticity, credibility and to identify any potential bias in the third phase of the document analysis process. In the fourth phase, the content of the collected documents was carefully examined, and the key themes and issues were identified and recorded. The fifth phase involved the deliberation and refinement to identify any difficulties associated with the documents, reviewing sources, as well as exploring the documents content. In the sixth and final phase, the analysis of the data was completed (O'Leary 2004).

In this study, all the gathered documents were downloaded and stored in a case study database (Yin 2018). The documents were all in English. Each document was carefully read, and key themes were coded and recorded (Baxter, 2021b).

IV. RESULTS

4.1 Frankfurt Airport: A Brief Overview

Frankfurt Airport is Germany's busiest airport and is one of the world's largest airports (Miyoshi & Prieto Torrell, 2019; Zintel, 2007). The airport is in Hesse at a location that was selected by the German government in 1936 (Niemeier, 2014). In addition to being a major passenger hub, Frankfurt is also a major European air cargo hub and is served by more than 20 cargo airlines. The airport is the major hub of Lufthansa Cargo. The airport frequently ranks amongst the major airports for international destinations served, with more than 100 airlines operating scheduled, charter and cargo services. Europe, the Middle East, Asia, Africa, South America, and North America are served directly by the airlines operating from Frankfurt (Centre for Aviation 2021). Frankfurt is the principal hub airport of German national carrier Lufthansa (Centre for Aviation 2021; Janić, 2017; Zintel, 2007).

Frankfurt Airport has two operating passenger terminals. Terminal 1 is divided into concourses A, B, C and Z and has a capacity of around 50 million passengers per year. Terminal 2, which has a capacity of 15 million passengers a year, was opened in 1994 and this terminal includes concourses D and E (Frankfurt International Airport, 2018). Frankfurt Airport has four runways: 07C/25C, 07L/25R, 07R/25L, and 18/36. The longest runway at Frankfurt Airport is Runway 07C/25C, which is 4,000 metres in length (Airport Guide, 2021). Frankfurt Airport has the terminal and runway infrastructure to handle the largest aircraft types in operation by the world's airlines, that is, the Airbus A380 and the Boeing 747-8 aircraft.

Frankfurt Airport is owned and operated by Fraport AG (Airport Technology, 2021). Fraport AG was founded in 1924, under the name Südwestdeutsche Luftverkehrs AG. The company originally operated Frankfurt Airport at the Rebstock site. Following the 1936 opening of Flug- and Luftschiffhafen Rhein-Main which is adjacent to the Frankfurter Kreuz autobahn intersection, the core of what is today's Frankfurt Airport (IATA airport code: FRA) began operations. Fraport AG is the owner of the airport site and provides the facilities to airlines and other key actors, including DFS German Air Navigation Services, as well as a large number of agencies and airport concessionaires (a total of more than 500 businesses and institutions) (Fraport AG, 2019).

At the time of the present study the major shareholders of Fraport AG were the State of Hesse (31.31%), Stadtwerke Frankfurt am Main Holding GmbH (20.48%), Deutsche Lufthansa AG (8.44%), and British Columbia Investment Management Corporation (3.05%) (Fraport AG, 2021b).

Fig.1: Frankfurt Airport's annual enplaned passengers and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020a)

Figure 1 presents Frankfurt Airport total annual enplaned (domestic and international) passengers and the year-on-year change (%) for the period 2008 to 2017. One passenger enplanement measures the embarkation of a revenue passenger, whether originating, stop-over, connecting or returning (Holloway, 2016). As can be observed in Figure 1, the growth in Frankfurt Airport's annual enplaned passengers has exhibited an upward trend, increasing from 53.4 million in 2008 to 70.5 million in 2019. Figure 1 also shows that there was a decrease in the number of passengers in 2009, when total passenger traffic declined by 4.74% on the 2008 levels. The global airline industry was adversely impacted by the global financial crisis (GFC) in 2008 and 2009, which resulted in a downturn in airline passenger demand (Morrell, 2013; Samunderu, 2020; Serebrisky, 2012). There was also a small decrease in enplaned passengers recorded in 2016 (-0.4%) at Frankfurt Airport (Figure 1).

Frankfurt Airport's total annual aircraft movements and the year-on-year change (%) are depicted in Figure 2. The aircraft movements at Frankfurt Airport include domestic and international commercial passenger flights, domestic and international commercial air cargo flights, domestic and international general aviation flights as well as State Aviation Flights, which may be operated domestically or internationally. As can be observed in Figure 2, the annual number of aircraft movements at Frankfurt oscillated quite widely during the period 2008 to 2019. The highest number of annual aircraft departures at Frankfurt Airport was recorded in 2019, when the airport handled 513,912 aircraft movements, this represented a 0.35% on the previous year's levels. Figure 2 shows that there was quite a pronounced spike in the annual aircraft movements at the airport in 2018, when they increased by 7.69% on the 2017 levels. The lowest annual number of aircraft movements occurred in 2016, when the airport handled a total of 462,885 aircraft movements. The fluctuations in the number of aircraft movements reflect airline operational patterns and passenger and air cargo demand profiles.

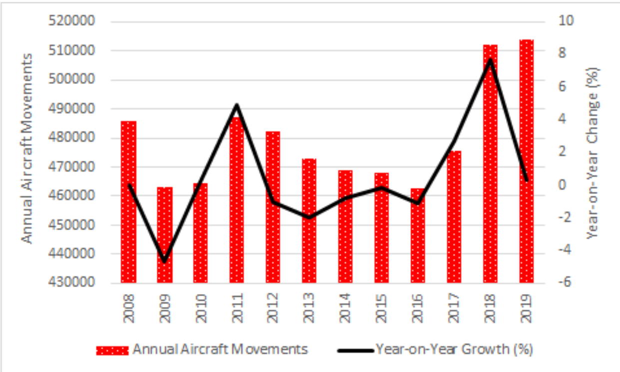

Fig.2: Frankfurt Airport's Frankfurt Airport's total annual aircraft movements and year-on-year change (%): 2008-2019: 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020a)

4.2 Frankfurt Airport Environmental Policy

Fraport AG has defined and implemented a comprehensive Environmental Policy. The core elements of the policy are as follows:

- In developing and operating all its business locations, Fraport AG is committed to manage all airport activities in an environmentally responsible manner. The company will strive to protect and create a safe living environment at all our business locations by providing the company's staff with healthy and safe working conditions.
- Fraport AG will maintain, develop and systematically improve its system of environmental management, which will follow the applicable laws and regulations, and this will lead to the continuous improvement of the company's environmental aspects.
- Fraport AG will undertake initiatives to promote greater environmental responsibility by training its staff and providing awareness programs for staff members at the company's various business locations.
- Fraport AG's business will support a precautionary approach to environmental challenges respecting the principle that its Environmental Programs will be cost-effective, economically viable and sustainable.
- Fraport AG will encourage the development and dissemination of environmentally friendly technologies by applying environmental criteria when selecting goods and services.
- Fraport AG will provide an annual environmental report that will outline the company's environmental activities and will make the information available to both staff members and the community (Fraport AG, 2020b, p.8).

The environmental policy is also underpinned by the company's climate protection, biodiversity, and stakeholder engagement principles (Fraport AG, 2020b).

4.3 Frankfurt Airport Management Regulatory Framework

In Germany, the Regulatory law stipulates that water bodies are subject to State management. Both citizens and authorities have an obligation to use water responsibly. The most important federal law in Germany is the *Federal Water Act* (Wasserhaushaltsgesetz, WHG, in German). This law originally came into effect in 1957. A substantially revised version came into force in March 2010. This latter amendment completed the transposition of the European Union (EU) Water Framework Directive (WFD) into German national law, and hence, enabled the German Länder to adapt their respective water acts to the European provisions. The amendment created the legal basis for transboundary, sustainable water management in Germany. Germany has a goal to achieve good status for all water bodies by 2027 at the latest, not just in terms of pollutant levels but also regarding the status of native aquatic animal and plant species. As a result, water management plans must be established. To coordinate this process, river basin communities have been established among the Länder. These bodies share the joint responsibility for the catchment areas of large rivers in the country (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2021).

According to the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (2021), "the *Federal Water Act* transposed the EU Floods Directive, the Marine Strategy Framework Directive and the provisions of the Industrial Emissions Directive that apply to water legislation in Germany". Germany also has other key ordinances regulating the implementation of the Federal Water Act. These include the Wastewater Ordinance (Abwasserverordnung, AbwV), the Surface Waters Ordinance (Oberflächengewässerverordnung, OGewV) and the Groundwater Ordinance (Grundwasserverordnung, GrwV). In Germany, these ordinances also implement important European Union (EU) provisions. The Groundwater Ordinance implements the European Union (EU) Groundwater Directive; the Surface Waters Ordinance implements the EU environmental quality standards for water bodies (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2021).

The long-term aims of Germany's water protection policy are:

- to maintain or restore good ecological and chemical quality of water bodies,
- to ensure an adequate supply of drinking and process water, both in terms of quality and quantity, and
- to secure for the long term all other water uses that serve the public interest. Such uses include leisure and recreation, shipping, and energy production (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2021).

4.4 Frankfurt Airport Water Infrastructure

Frankfurt Airport is making greater use of rainwater, treated water from the River Main, as well as well water. This has resulted in a reduction in the consumption of drinking water at the airport. Fraport operates several facilities for treating rainwater. These facilities turn rain- and groundwater into processed water. Water from the River Main is fed into the treatment facilities during the times where there is low rainfall to ensure an adequate supply of processed water. The airport has been steadily expanding its use of this kind of water (Fraport AG, 2021a). Water saving technologies are used in the airport's sanitary system and circulatory systems are used in the vehicle washing systems. Frankfurt Airport ensures wherever possible that drinking water is replaced by service water (Fraport AG, 2020a).

As the airport operator, Fraport AG has the responsibility to operate and utilize drainage networks at the airport. The company operates two separate sewer systems for waste and rainwater to keep capacity utilization in the sewage treatment plants constant and prevent them from being overloaded by large volumes of rainwater (Fraport AG, 2021a). The separation of sewage water and precipitation water relieves the pressure on the sewage treatment plants operating at Frankfurt Airport. Fraport AG operates two separate drainage systems: one for sewage water and one for precipitation water. A key advantage of this approach is that the capacity of the sewage systems is utilized at a more consistent rate and is not placed under pressure by large volumes of rainwater. Furthermore, the risk of overloading sewage water drainage pipes is also avoided during storms that have heavy levels of rainfall (Fraport, 2020a). The airport's sewage water system has pipework measuring around 100 kilometres in length. The sewage system accepts all the discharges from sanitary facilities, canteens, restaurants, tunnel washers, aircraft restrooms, and aircraft washing equipment. The precipitation water drainage system has a length of approximately 200 kilometres and this system is used to drain the rainwater from aprons, aircraft positions, deicing areas, roads, parking lots and roofs. As part of new construction at the airport, precipitation water is increasingly being removed from unpolluted roof surfaces via rain drains with the goal of exerting a positive impact in the replenishment of ground water. The sewage water drains into the public drainage system at two points and is pumped to the municipal treatment plants in Sindlingen and Niederrad. Fraport AG operates its own sewage treatment plant in the southern section of the airport. This plant has a capacity of 100,000 population equivalents. The sewage plant treats around 1.4 million cubic metres of sewage water each year. The sewage water from the entire southern section of the airport is treated at the plant together with the wastewater containing deicing agents from aircraft movement areas (Fraport, 2020b). In regions where temperatures drop below freezing point, aircraft surfaces must be de-iced prior to take-off to ensure that the wing control surfaces can function and the aerodynamic properties of the wing are not changed by ice (Marais & Waitz, 2009).

Due to the growth in the use of service water at Frankfurt Airport, Fraport operates several rainwater treatments plants that are located in the CargoCity South precinct and in Terminals 1 and 2. The airport's new Pier A-Plus terminal has also been equipped with a rainwater treatment plant. The service water at Frankfurt Airport is sourced from rainwater and groundwater (well water). When rainfall levels are low, purified water from the River Main is used at the airport. The service water is sourced through separate supply networks and is used for sprinkler systems, toilet flushing and for watering of the airport's landscaped areas. A complete service-water supply system is used in the airport's CargoCity South precinct. In the north of the airport, Terminals 1 and 2 are supplied with service water (Fraport, 2020b).

After flowing through the sludge removal tanks, rainwater from the apron and airport operational areas is passed through oil separators to remove potential contaminants from risk areas, for example, aircraft refueling. The permissible run-off water volumes are guaranteed by rainwater retention basins. The water is only then channeled into the River Main, the Creek Gundbach or passed into infiltration plants where the purification process is completed. Systematic checks are performed to establish compliance with the specified tolerance limits (Fraport, 2020b).

Water management at Frankfurt Airport also includes the drainage systems installed in the Runway Northwest precinct. In this area, the precipitation water from the runway, which is only used for aircraft landings, and its taxiways flows along slot channels configured along the sides of traffic surfaces, where it is passed through a network of drains 23 kilometers in length. The water is subsequently pumped into two underground reservoirs, each with a capacity of 12,500 cubic meters. The water then passes through filters with a total area of 20,000 square meters and deicing agents are removed during the winter months. Extinguishing water retention, treatment and discharge are included in all new planning approvals for buildings at the airport. This affects systems for treating substances harmful to water that are included under the scope of the Extinguishing Water Retention Directive (LöRüRL) and the Plant Regulations (Fraport, 2020b).

Wastewater at Frankfurt Airport is treated in the airport's fully biological treatment plant, as well at the fully biological water treatment plants in Frankfurt Niederrad and Frankfurt Sindlingen (Fraport AG, 2020b).

At Frankfurt Airport, grease, and oil separators, and demulsification plants are positioned where wastewater is generated and is processed before the water is discharged into the drainage system. These installations restrict the entry of polluting substances into the drainage channels and treatment plants. Frankfurt Airport has included a requirement for the compliant operation of fat separators in new contracts for concessionaires of food and beverage units. The purpose of this is to protect the fat separators and more extensive cleaning systems against overloads or impact loads of sewage water containing fat or disinfection agents (Fraport, 2020b). Airport concession operations include the running or leasing out of shopping concessions of various kinds, car parking and rental, banking and restaurant/catering establishments (Zhang & Zhang, 1997).

To ensure sustainable management of the dewatering system in an area where dewatering pipes may be coated with fuel, positive-locking sleeve-fitted HDPE pipes are used in all newbuilds, for example, at remote aircraft stands. Welded pipe connections are permanently sealed-tight. The water consumption for drainage cleaning and flushes can therefore be reduced because of the smoother surfaces (Fraport, 2020b).

The safety of air transport operations also requires that runways/taxiways and aircraft are kept free of both ice and snow. To ensure the safe landing and take-off of aircraft, independent of the prevailing weather conditions at the airport, aircraft de-icing/anti-icing fluids (ADFs) and runway de-icing chemicals are often required (Breedveld et al, 2003, p. 91). Potassium formate is used in the airport's aircraft deicing movement areas in concentrations to match the prevailing weather conditions. The deicing agents are readily biologically degradable within a short space of time and satisfy stringent environmental requirements. Precipitation water containing deicing agent from drained surfaces is retained and treated in the airport's water treatment facilities (Fraport, 2020b).

In addition, there is systematic monitoring which analyzes the quality and volumes of the wastewater flows to ensure that applicable limits are complied with (Fraport AG, 2021a). Fraport AG regularly conducts measurements of chemical and physical parameters in the wastewater at the confluence points and the wastewater units to guarantee that no pollution occurs. The precipitation water is continuously monitored by the airport at the discharge points in the River Main and the central seepage installations (Fraport, 2020b).

4.4 Frankfurt Airport Water Consumption

Frankfurt Airport's annual water consumption and the year-on-year change (%) from 2008 to 2019 are presented in Figure 3. As can be observed in Figure 3, the airport's annual water consumption has largely exhibited an upward trend, which is inline with passenger and aircraft movements growth throughout the study period. This upward trend is demonstrated by the year-on-year percentage change line graph, which is more positive than negative, that is, more values are above the line than below. Figure 3 shows that there were three years during the study period, when the annual water consumption decreased on a year-on-year basis. These decreases were recorded in 2009 (-10.21%), 2015 (-9.94%), and 2016 (-0.95%) (Figure 3). There were two quite pronounced spikes in water consumption at the airport and these occurred in 2010 (+15.44%), and 2018 (+22.67%). These increases reflected greater water consumption patterns in those years.

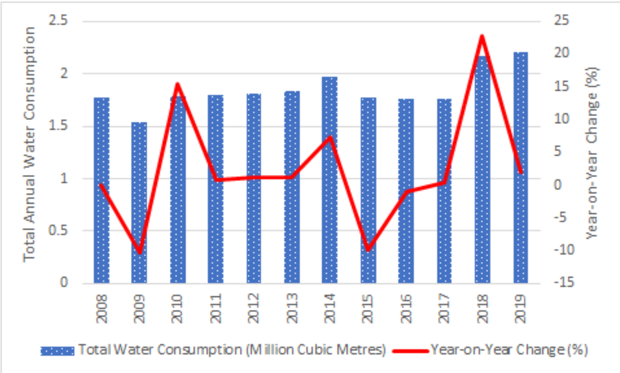

Fig.3: Frankfurt Airport's annual water consumption and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

An important environmental related efficiency metric used by airports is the annual water consumption per enplaned passenger (Graham, 2005) or per workload unit (WLU). One workload (WLU) or traffic unit is equivalent to passenger, or 100 kilograms of air cargo handled (Doganis, 2005; Graham, 2005; Teodorović & Janić, 2017). Frankfurt Airport's annual water consumption per workload unit (WLU) and the year-on-year change (%) from 2008 to 2019 are presented in Figure 4. Figure 4 shows that annual water consumption per workload (WLU) remained within a range of between 20.43 litres to 24.17 litres per workload unit (WLU). The highest annual water consumption per workload unit (WLU) was recorded in 2019 (24.17 litres/WLU), whilst the lowest level in this metric was recorded in 2017 (20.43 litres/WLU). There were five years throughout the study period where there were year-on-year decreases in the levels of water per workload unit (WLU). These decreases were recorded in 2009 (-6.72%), 2011 (-2.96%), 2015 (-11.06%), 2016 (-1.05%), and 2017 (-4.84%), respectively. The largest single annual increase in this metric occurred in 2018, when the annual water consumption per workload unit (WLU) increased by 16.15% on the 2017 level. As previously noted, Frankfurt Airport has recorded strong growth in its passenger traffic throughout the study period and, as such, this metric is influenced by the discrete water requirements of the passengers using the airport.

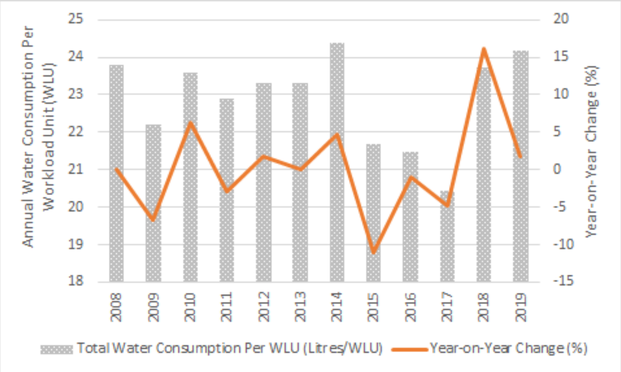

Fig.4: Frankfurt Airport's annual water consumption per workload unit (WLU) and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

Another important airport environmental-related metric used in the airport industry is the annual water consumption (cubic metre) per aircraft movement (Baxter et al., 2018). Figure 5 depicts Frankfurt Airport's annual water consumption per aircraft movement together with the year-on-year change (%) for the period 2008 to 2019. As is evident in Figure 5, there has been an overall upward trend in the annual water consumption per aircraft movement at Frankfurt Airport. The annual water consumption per aircraft movement increased from 3.65 cubic metres per aircraft movement in 2008 to 4.30 cubic metres per aircraft movement in 2019. The general upward trend is demonstrated by the year-on-year percentage change line graph, which is more positive than negative, that is, more values are above the line than below. During the study period, there were four years when the annual water consumption per aircraft movement decreased on a year-on-year basis. These decreases occurred in 2009 (-8.76%), 2011 (-3.91%), 2015 (-9.76%), and 2017 (-2.36%). The largest single annual increase in water consumption per aircraft movement was recorded in 2018 (+14.01%). It is important to note that the size of commercial aircraft have increased in recent times. The Airbus A380 entered commercial service with Singapore Airlines in 2007 (Jackson, 2021; Simons, 2014). The Boeing 787-8 entered commercial service in 2011 (Saha, 2016). The Airbus A350-900XWB first commercial flight was operated by Qatar Airways in 2014 (Aircraft Commerce, 2015). Singapore Airlines took delivery of the first Boeing 787-10 on March 14th, 2018 (Boon, 2020). The Boeing 787-8 is around 20 seats larger than the Boeing 767-300ER, whilst the Boeing 787-9 has about 20 seats more capacity than the A330-200 (Aircraft Commerce, 2016). Importantly, depending upon aircraft size, the total water uplift on a flight can be more than 2,000 litres (Franzi, 2017). Thus, the trend towards larger aircraft types has a concomitant impact on the level of water that needs to be uplifted on the flight in accordance with airline potable water policy requirements.

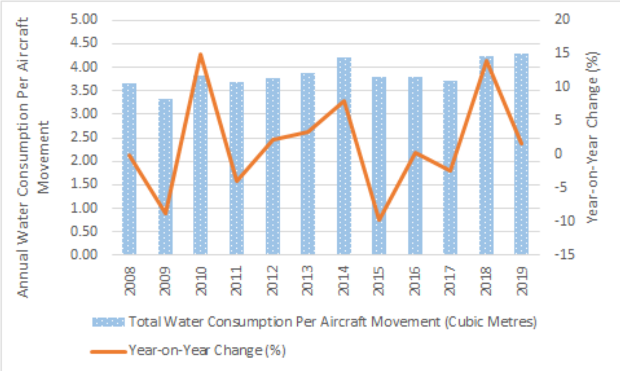

Fig.5: Frankfurt Airport's annual water consumption per aircraft movement and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

At Frankfurt Airport, drinking water is sourced from the local authority water supply (Fraport AG, 2020). Frankfurt Airport's annual drinking water consumption and the year-on-year change (%) from 2008 to 2019 are presented in Figure 6. As can be observed in Figure 6, the annual drinking water consumption at Frankfurt Airport fluctuated over the study period. The lowest level of drinking water was recorded in 2009 (1.336 million cubic metres), whilst the highest level was recorded in 2014 (1.624 million cubic metres) (Figure 6). Figure 6 shows that in the latter years of the study, that is, from 2014 to 2019, there was a general downward trend, with annual decreases recorded in 2015 (-11.88%), 2016 (-4.05%), and 2017 (-7.21%). This was a favorable trend given the increase in the passenger traffic growth in this period. In 2018 and 2019, the annual water consumption rose slightly, reflecting the greater number of passengers using the airport in those years. Figure 6 shows that there was a pronounced decrease in 2009, when the airport's total annual drinking water decreased by 15.49% on the 2008 levels. This was the most significant annual decrease recorded in the study period. The highest annual increase in drinking water consumption occurred in 2014, when the annual drinking water consumption increased by 9.58% on the 2013 levels (Figure 6). There were six years in the study period where Frankfurt Airport's annual passenger volumes increased whilst at the same time the amount of drinking water decreased. This pattern occurred in 2009, 2011, 2013, 2015, and 2017. In 2018, passenger traffic grew by 7.75%, whilst the annual drinking water consumption increased by 5.65%, which is a favorable outcome. In contrast, in 2012 passenger traffic grew by 1.91% and drinking water consumption by 5.25%. Also, in 2019, passenger traffic grew by 1.5%, whilst the annual drinking water consumption increased by 7.57%, reflecting differing customer water consumption in these years.

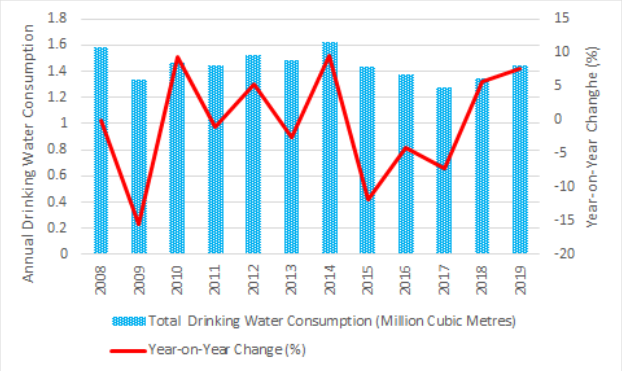

Fig.6: Frankfurt Airport's annual drinking water consumption and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

At Frankfurt Airport, the service water is treated from surface water, rainwater, and groundwater (Fraport AG, 2020). Figure 7 presents Frankfurt Airport's annual service water consumption together with the year-on-year change (%) from 2008 to 2019. Figure 7 shows that the service water consumption at Frankfurt Airport has largely exhibited an upward trend, increasing from 0.191 million cubic metres in 2008 to 0.76 million cubic metres in 2019. During the study period, there were three pronounced increases in the airport's service water consumption. These spikes were recorded in 2010 (+55.6%), 2013 (+20.74%), and 2018 (+66.93%), with these increases reflecting additional service water requirements in those years (Figure 7). Figure 7 shows that there were four years during the study period when the airport's annual service water consumption decreased on a year-on-year basis. These decreases occurred in 2012 (-15.51%), 2014 (-2.53%), 2015 (-0.86%), and 2019 (-7.09%), respectively. The key actors operating at Frankfurt Airport influence the service water consumption, and Figure 7 highlights the fluctuations in these actors' demand for service water, which are influenced by differing annual demand requirements.

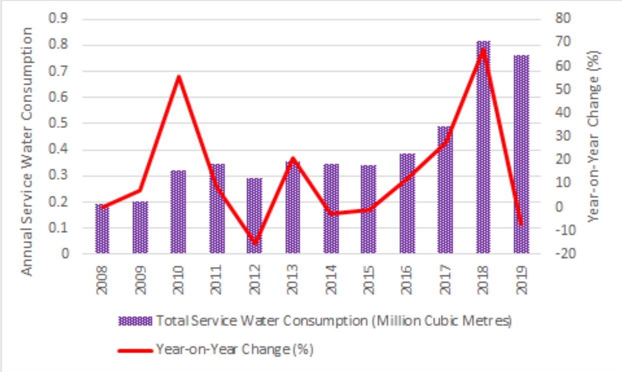

Fig.7: Frankfurt Airport's annual service water consumption and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

4.5 Frankfurt Airport Sewage Waters

The sewage waters at Frankfurt Airport originate from Fraport AG, the parent company, plus another 500 companies who have operations at the airport (Fraport, 2020). Frankfurt Airport's annual sewage waters and the year-on-year change (%) for the period 2008 to 2019 are presented in Figure 8. Figure 8 shows that there were three discernible trends in Frankfurt Airport's annual sewage waters throughout the study period. There was a general upward trend in these waters from 2008 to 2013, when they increased from 1.548 million cubic metres in 2008 to a high of 2.253 million cubic metres in 2013. There was a significant decrease recorded in 2014 (-31.86%). From 2014 to 2019, there was a general upward trend in the airport's sewage waters, when they increased from 1.535 million cubic metres in 2014 to 2.142 million cubic metres in 2019 (Figure 8). Figure 8 shows that there were two pronounced spikes in these annual water volumes. The significant increases occurred in 2010 (+17.69%), and 2015 (+29.38%), respectively. Figure 8 also reveals that there were pronounced decreases recorded in 2009 (-12.72%), and 2014 (-31.86%). As previously noted, there has been a significant growth in passenger traffic and aircraft movements, and thus, the greater passengers' volumes and aircraft movements can have a concomitant increase in sewage waters. From 2013 onwards, the separation of precipitation water that is contaminated with de-icing agents that are used in the winter months to de-ice aircraft has resulted in an increased dependence of the amount of sewage water and this is influenced by the winter weather conditions (Fraport AG, 2020b).

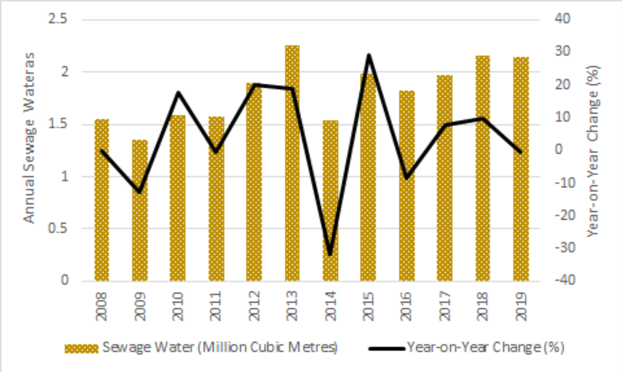

Fig.8: Frankfurt Airport's annual sewage waters and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

Frankfurt Airport's annual sewage waters per workload unit (WLU) and the year-on-year change (%) from 2008 to 2019 are presented in Figure 9. As can be observed in Figure 9, there was a general upward trend in the annual sewage waters per enplaned passenger from 2008 to 2013, when they increased from 20.8 litres per workload unit (WLU) in 2008 to a high of 28.6 litres per workload unit (WLU) in 2013. Figure 9 shows that Frankfurt Airport's annual sewage waters per workload unit (WLU) decreased significantly in 2014, when they decreased by 33.53% on the 2013 levels. From 2016 to 2019, there was a small upward trend in the annual sewage waters per workload unit (WLU). Figure 9 also shows that there were three quite significant spikes in this metric, with these increases occurring in 2012 (+20.29%), 2013 (+17.69%), and 2015 (+27.82%), respectively. Figure 9 shows that the airport's annual sewage waters per workload unit are closely associated with increases in passenger traffic, which has the associated effect of producing more sewage waters.

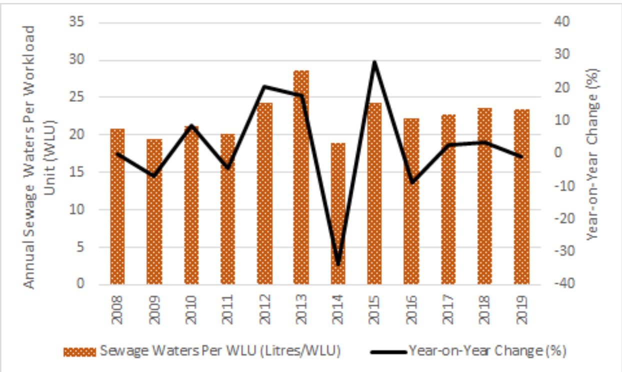

Fig.9: Frankfurt Airport's annual sewage waters per workload unit (WLU) and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020b)

V. CONCLUSION

One of the most widespread trends in the global airport industry in recent times has been the increased focus by airports on the sustainable management of their water consumption and the discharge of waste waters. Consequently, sustainable water management has assumed greater importance for airports all around the world. This increased focus on sustainable water management by airports is in recognition that airports consume large amounts of water, which therefore requires careful management. In addition, airports often generate significant volumes of waste and drainage waters, which needs to be processed in an environmentally friendly manner. This study has empirically examined the annual water consumption at Frankfurt Airport, Germany's busiest airport, and a major global hub airport. The case study also examined how the increases in air traffic and aircraft movements at the airport recorded throughout the study period have influenced water consumption at Frankfurt Airport. To achieve the study's research aim, Frankfurt Airport was selected as the case airport. The study's research was underpinned by an-in depth qualitative longitudinal research design. The data collected for the study was analyzed by document analysis. The study period was from 2008 to 2019.

The case study found that Frankfurt Airport's annual water consumption, water consumption per workload unit (WLU) and water consumption per aircraft movement largely exhibited an upward trend over the study period. As previously noted, Frankfurt Airport recorded strong growth in passenger traffic and aircraft movements during the study period. In addition, there has been growth in the size of the aircraft deployed by airlines that provide air services to and from Frankfurt Airport.

The annual consumption of drinking water fluctuated over the study period due to differing consumption patterns. The highest drinking water consumption was recorded in 2008 (1.581 million cubic metres), whilst the lowest annual drinking water consumption was recorded in 2017 (1.274 million cubic metres).

The annual service water consumption showed an upward trend, increasing 0.191 million cubic metres in 2008 to 0.76 million cubic metres in 2019.

The case study revealed that the annual sewage waters oscillated over the study period. The highest annual sewage waters volume was recorded in 2013 (2.253 million cubic metres), whilst the lowest annual sewage water volumes were recorded in 2009 (1.351 million cubic metres). There was an overall general upward trend in the sewage waters per workload unit (WLU), which increased from 20.8 litres/WLU in 2008 to 23.4 litres/WLU in 2019.

Sustainable airport water management requires the use of infrastructure and various technologies such as water processing plants and systems for capturing chemicals and aircraft de-icing agents that could potentially contaminate the water resources within the airport as well as local rivers, streams, or lakes. Frankfurt Airport has installed and extensively uses such infrastructure. Frankfurt Airport operates its own sewage treatment plant. Wastewaters generated at the airport are treated in Frankfurt Airport's fully biological water treatment together with the fully biological water treatment plants in Frankfurt Niederrad and Frankfurt Sindlingen. Frankfurrt Airport also operates several rainwater treatment plants. Other important sustainable water-related infrastructure includes the grease and oil separators and demulsification plants.

The case study found that Frankfurt Airport is making greater use of rainwater, treated water from the River Main, as well as well water. As part of its sustainable water management practices, Frankfurt Airport uses water saving technologies in the airport's sanitary system. Frankfurt Airport ensures wherever possible that drinking water is replaced by service water. Frankfurt Airport systematically monitors the quality and volumes of the wastewater flows at the airport to ensure that applicable limits are always complied with.

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