

# Application of Two-Component Sprayed Polyurea Membrane for Improving RCC Dam Watertightness

G. Pietrangeli, G. Pittalis & A. Cagiano

*Studio Ing. G. Pietrangeli, Rome, Italy*

**ABSTRACT:** Excessive leakages and/or uplifts through RCC dams may occur due to preferential seepage paths through localized defects in joints between lifts, upstream facing and contraction joint watertight system. Risks associated with these defects, generally difficult to identify before impounding, are more significant for high dams, particularly below the minimum operating level, where remedial works are inherently complex and expensive.

This paper discusses the use and characteristics of Spray-Applied Waterproofing Membranes (SWMs), and particularly the two-component polyurea, as an advanced method for improving RCC dam watertightness.

The main feature of SWMs is their capacity to adhere tightly to the substrate, forming a fully bonded continuous layer that increases the overall watertightness of the upstream face at the large scale. A key element for the successful implementation of SWMs is the correct preparation of the substrate, including removal of dirt, laitance, anti-evaporation compounds, traces of form release agents, control of humidity, etc.

SWM technology can effectively contribute to the long-term performance of RCC structures, considering its excellent bond strength, continuity of watertightness, installation flexibility, and crack bridging ability. The main challenges are related to quality control during installation (as is common for all the in-situ manufactured elements) which must guarantee the correct substrate preparation and the required membrane thickness.

## 1 SPRAY-APPLIED POLYUREA MEMBRANES

### 1.1 *Spray-applied Waterproofing Membranes*

Spray-applied Waterproofing Membranes (SWMs) cover a broad range of materials that can be subdivided according to their film forming mechanisms into two main categories:

- Non-reactive systems, in which the membrane is formed through the evaporation of the solvent (in solvent-based systems) or water (in water-emulsion systems)
- Reactive systems, in which the membrane is formed through polymerization and cross linking of two or multi-component materials.

The key and common characteristic of SWMs is their ability to adhere tightly to the substrate, forming a fully bonded, seamless layer that enhances the overall watertightness of the sprayed subgrade.

Since there are no gaps between the sprayed membrane and the substrate, and no joints within the membrane or at the membrane-substrate interface, any localized defect or damage occurring during construction or service will not compromise the overall permeability of the system, therefore significantly reducing the probability of water seepage.

As the membrane is sprayed directly onto the support to form a seamless film, the system offers evident advantages and high adaptability in geometrically complex areas such as niches, cross passages, and other irregular surfaces. The membrane thickness can also be easily locally adapted to meet specific design requirements. Moreover, the system can be used in combination with other waterproofing systems, such as standard movement joints or sheet membranes, providing considerable design and construction flexibility.

Especially in tunnel applications, the membrane can be sprayed over the primary lining and subsequently covered by a secondary lining. Depending on the design requirements and the selected product, the membrane may bond to both the primary and secondary linings (double bonding) or to only one lining (single bonding). In the case of a spray applied membrane with double-bonding properties (generally constituted by a Ethylene-Vinyl-Acetate polymer), the resulting concrete-membrane-concrete sandwich-structure may behave as a quasi-monolithic system (composite shell lining), potentially allowing savings in the structural design of the lining (ItaTech, 2013; Pillai 2017).

Additional features of reactive systems include rapid polymerization, which allows application also in vertical surfaces, as well as high chemical resistance and mechanical properties (including elongation, crack-bridging ability, tensile and tear strength, abrasion resistance, adhesion to different time of supports, etc.) and thermal stability.

Despite these advantages, SWMs technology has also limitations, primarily related to the fact that in-situ produced membranes requires close and systematic quality control during construction to ensure adequate adhesion, thickness and coverage. Environmental conditions, as well as a rigorous support preparation and controlled application procedures, are critical to achieve the desired adhesion strength. Under certain conditions, such as high humidity, water inflow or poor support conditions, application of SWMs may be impractical.

For these reasons pre-production trials and onsite quality assurance procedures, including adhesion testing and layer thickness verification, are essential to ensure consistent performance across varying site conditions.

## 1.2 Chemistry of spray-applied polyurea

The first polyurea products were developed and commercialized in the late 1980s in the United States, from where they rapidly spread worldwide, where they experienced significant growth since the second half of the 1990s. Due to their excellent flexibility, tensile properties, adhesion, chemical resistance and environmental compatibility, the use of polyurea elastomeric coatings in the civil and industrial waterproofing and protection applications is broad and constantly evolving, fostering the creation of technical industry associations such as the Polyurea Development Association (PDA), established in 1999 in USA and 2005 in Europe. PDA serves as a center for the development and promotion of polyurea applications and their safe and proper use, providing codes of good practice, list of certified applicators, and collection of case studies.

Market data and industry estimate indicate that the global polyurea production is valued at approximately 1 billion USD, with Europe accounting for about 25% of the market share. Approximately 30% of the market is dedicated to civil construction applications, including concrete coatings of buildings, bridges, parking decks, underground structures, water-retaining structures, wastewater treatment plants, secondary containment, canals, etc.

It should be emphasized that the term “polyurea” refers to a technology rather than a single material, and a variety of different formulations can be used depending on the desired target properties to be achieved. A basic distinction should be made between pure polyurea and hybrid polyurea system. Pure polyurea should not contain hydroxyl groups in its formula, whereas hybrid systems are characterized by the presence of OH groups and catalysts, representing a kind of combination between polyurethane and polyurea.

Polyurea is an elastomer obtained through the polyaddition reaction of a polyfunctional isocyanate with a polyfunctional amine, generally in a 1:1 volumetric mixing ratio. The reaction of polyamines and isocyanates (which forms polyurea) is highly exothermic and is schematically illustrated in the figure below.

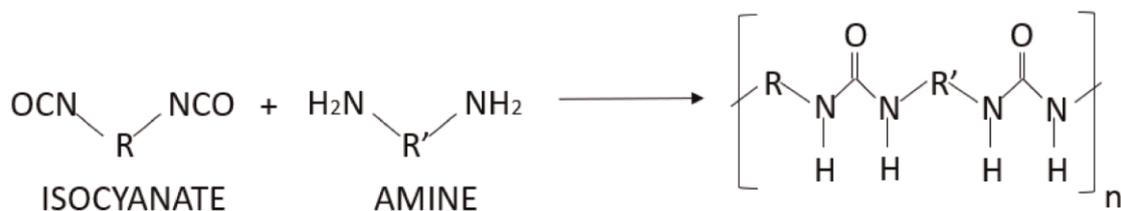


Figure 1 – Polyurea reaction

A higher content of NCO-groups in the isocyanate, which constitutes the hard segment of the chain, results in lower viscosity, higher reactivity and lower elasticity. Generally, for standard formulations, the NCO-group content ranges from 8 to 20 %, with a typical value of 15% on isocyanate component.

The amine component of polyurea primarily consists of:

- high molecular polyamines, which constitute the soft segment of the chain
- low molecular weight polyamines, which act as chain extenders

The choice of the amines is crucial for both processing and final performance of the polyurea.

The nature of the R-group in the isocyanate has also a significant influence, with aromatic isocyanates typically showing higher reactivity but lower UV resistance, whereas aliphatic isocyanates provide significantly improved UV stability and color retention.

Thanks to the high reactivity between isocyanates and amines, no catalysts are necessary for the reaction of pure polyurea systems. The high reactivity also ensures a very fast setting with the formation of a continuous film that attains its final mechanical properties in about 24 hours, making the polyurea suitable to be sprayed also over vertical surfaces. The formation of the urea groups generates a very high number of intermolecular hydrogen bonds, resulting in excellent mechanical properties, including high elasticity, tensile strength tear resistance and thermal stability.

Typical mechanical characteristics of commercially available pure polyurea are reported in the table below:

Table 1 – Typical basic characteristics of pure polyurea

	UNIT	standard	
Density	g/cm <sup>3</sup>	EN 1183-1	1.1
Isocyanate/Amine ratio	-	-	1/1 (by weight and volume)
Gel Time	sec	-	~10
Tensile Strength	N/mm <sup>2</sup>	ISO 37	> 20
Elongation at failure	%	ISO 37	> 300
Tear Strength	N/mm	ISO 34-1	> 80
Direct traction adherence	N/mm <sup>2</sup>	EN 1542	> 3
Static crack bridging	-	EN 1062-7	Class A5 (> 2.5mm)
Shore hardness A/D	-	DIN 53505	> 90 / > 40

Another important feature of polyurea technology is its 100% solids nature, with no volatile organic compounds (VOC’s). As a result, solvent emissions are eliminated and, when properly processed, the release of vapors and fumes during application is minimized, although adequate protective measures are required, with no emissions after curing.

### 1.3 Basic Application Procedures

The preparation of the substratum surface is of fundamental importance for the successful application of any sprayed membrane system. The operating cycle for a concrete substrate and sprayed polyurea generally includes the following steps:

- Any laitance, loose material, oil, grease, or other contaminants on the dam face shall be completely removed by grinding, sandblasting, water jetting or other suitable methods.
- Any voids, honeycombing, surface defect and irregularities shall be repaired with an appropriate system.



Figure 2 – Gibe III RCC dam (Ethiopia), detail of U/S GERCC after cleaning with pressurized water (200 bar)

- A promoter of adhesion (primer) shall be applied, to be selected according to substrate's condition and its residual moisture
- Prior to membrane application, the concrete surface must be adequately de-dusted with an industrial vacuum cleaner.
- The temperature of the substrate must be at least 3°C higher than the dew-point temperature, and the residual moisture content of the concrete shall not exceed 4%.
- The membrane shall be sprayed onto the prepared surface to the required thickness (in the range of 4 mm, according to author's experience). The membrane shall be sprayed in a single pass to obtain a continuous, uniform and seamless film with the required thickness. If multiple applications are required to cover the entire surface, a primer coat shall be applied over the overlap sections to ensure full adhesion and continuity.

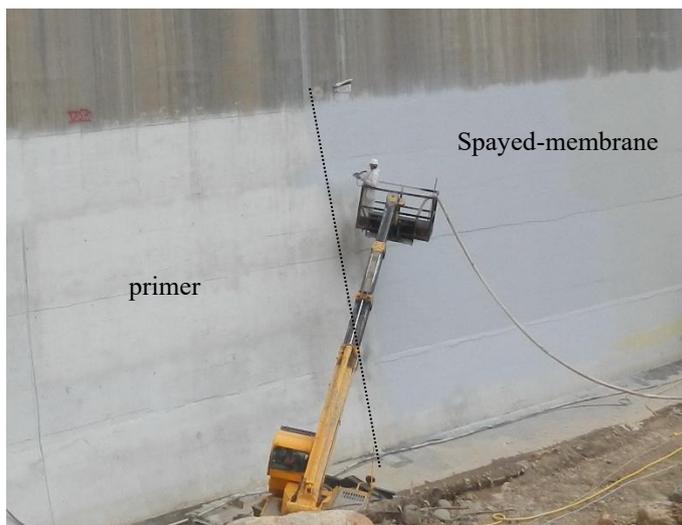


Figure 3 – Gibe III RCC dam (Ethiopia), application of sprayed-membrane

- Depending on the type of sprayed-membrane and exposure, a suitable protective coating (generally an aliphatic polyurethane compound) shall be applied over the membrane after its installation. Specific design solutions are required in correspondence of movements joints, often involving the local use of sheet membranes or other sealing elements, depending on the joint characteristics in terms of opening, expected movements etc.

While polyurea is not classified as dangerous in its polymerized state, appropriate precautions must be adopted during the handling and spraying of polyamine and isocyanate.

Qualified and trained personnel (adequately protected with safety glasses, chemical resistant gloves and clothing, respiratory protection, etc.) must be employed to operate these materials and the high pressure (150-250 bars) spraying machines.

The application system consists of two supply pumps, inserted into the drums containing the isocyanate and polyamine components and controlled by a control unit, which can be either pneumatic, hydraulic or electric. Isocyanate lid is provided with a dehumidifying filter to prevent ingress of humid air; polyamine drum is equipped with an agitator to homogenize the product. The components are heated by dedicated electrical heaters to a temperature generally between 50° C and 80° C to ensures proper mixing, fast and complete reaction, and the formation of a high-quality polyurea coating. The chemicals are pumped through heated hoses to the spray-gun where they mix immediately before the discharge nozzle. Due to the extremely short reaction time (typically in the order of a few seconds), polymerization begins almost instantaneously upon spraying. The flow rate of commercially available pump is generally between 3 and 12 litre per minute.

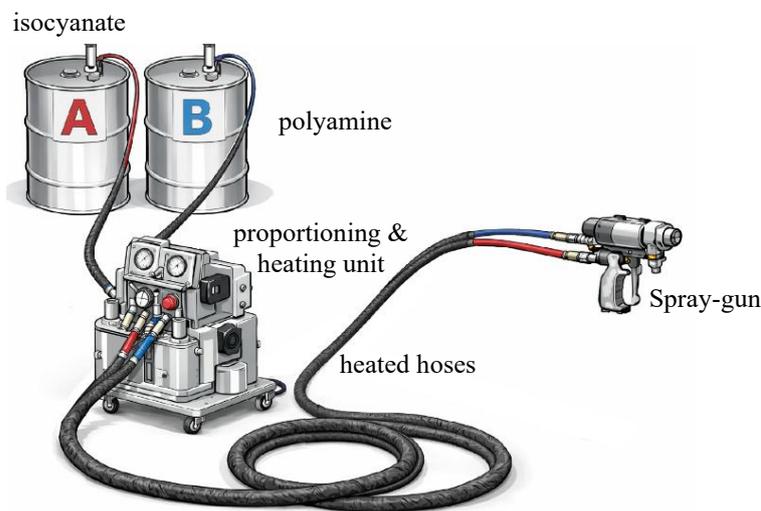


Figure 4 – Typical two-component polyurea spray system

With the typical setup described above, a three-person team can achieve a daily production rate of approximately 1,000 m<sup>2</sup> when applying the system to a dam face.

## 2 APPLICATION of SPRAY-APPLIED POLYUREA for CONCRETE DAMS

### 2.1 General

As previously indicated, the first polyurea products were developed and commercialized in the late 1980s in the United States. To the author's knowledge, the first applications of spray-applied polyurea for crack repair and as an additional anti-seepage protective lining for dams date back to the early 2000s. Major projects include the Xin'anjiang Dam (China), Fengman Hydropower Station (China), Nierji Dam (China), Xiluodu High Arch Dam (China), Girotte Dam (France), Gibe III Dam (Ethiopia), Saretto Dam (Italy), San Andrés Dam (Spain), the Tokwe Mukorsi Tunnel (Zimbabwe), and the Cave del Predil Canal (Italy).

Due to their relatively recent and still limited use in dams engineering, in-situ manufactured membranes are only briefly mentioned in the ICOLD bulletins addressing geomembrane sealing systems (bulletins No. 78 dated 1991 and No. 135, dated 2010). In these documents, they are classified as coatings closely related to resin-based systems and are noted as having limited application. The site-produced membranes referred to in these bulletins do not include modern polyurea systems; rather, they consist of *hot or cold applied liquid products used to impregnate a geotextile previously laid on the supporting layer.*

Spray-applied polyurea, however, represents a promising technology for effectively reducing dam leakages and uplifts, thereby contributing to the long-term performance of concrete structures and RCC dams. Excessive leakages and uplifts through RCC dams may develop due to preferential seepage paths through localized defects in joints between lifts, upstream facing and contraction joint watertight system.

The risks associated with these defects, generally difficult to identify before impounding, are more significant as the height of the dam and the water-head increase, particularly in the lower part of the dam, below the minimum operating level of the control structures (e.g. Low Level and Bottom Outlets), where remedial works are inherently complex and expensive.

When the substrate is correctly treated and the sprayed polyurea is properly applied, the resulting bond creates a continuous composite element, such that failure in adhesion tests is consistently observed within the concrete substrate, rather than at the membrane/concrete interface.

The ability of the spray-applied polyurea to form a fully bonded continuous, impervious and seamless layer, combined with its high elongation and crack bridging capacity, increases the overall watertightness of the dam face at the large scale, effectively reducing leakages and uplifts and contributing to the long-term structural performance of the dam.

Moreover, as there are no gaps between the sprayed membrane and the substrate, and no joints within the membrane or at the membrane-substrate interface, any localized defect or damage occurring during construction or service does not compromise the overall permeability of the system, therefore significantly reducing the probability of water seepage.

Due to the critical influence of site conditions (environmental, substrate properties, installation methodology and procedures) on spray-applied polyurea performance it is however necessary to plan a comprehensive site and laboratory investigation program, tailored to project needs, to ensure consistent performances.

## 2.2 *Site and laboratory tests*

Commercially available products generally comply with most severe classes specified in reference standards for concrete protection, including EN 1504-2 (*Surface protection systems for concrete*), EN 1062-7 (*Crack bridging properties*), EN 1297 (*Artificial aging*).

However, it should be noted that the testing conditions prescribed in the above standards may not be fully representative of actual site conditions of a concrete dam, in particular:

- Pull-off tests are typically performed on a membrane applied to a standardized concrete support, whose characteristics may differ significantly from those of a RCC dam facing.
- Polyurea membranes are applied to the substrate in fully bonded condition, therefore free film elongation tests do not provide representative information on in-situ behaviour
- Crack-bridging ability is determined without the application of hydrostatic pressure, which is clearly not representative of in-service conditions.

For the above reasons specific tests were carried out on site and in CESI laboratories (Italy) to evaluate the sprayed-polyurea used in the lowest part of Gibe III RCC dam (Ethiopia), namely the two-component, solvent-free pure polyurea membrane “Purtop 1000” produced by Mapei.

To verify the ability of the membrane to bridge possible cracks that may develop on the RCC surface, the behaviour of the membrane was evaluated by generating a 4 mm crack in the substrate while applying, at the same time, a pressure of 25 bar. A film of Purtop 1000 was therefore applied to a pre-notched steel disc, on which a 4 mm crack was subsequently opened. The disc was then placed inside a pressure chamber that applied positive pressure from 0 to 25 bar for a period of 7 days. At the end of the test, the membrane showed no signs of damage or leakage, despite a reduction in thickness from 2.16 mm to 1.75 mm.

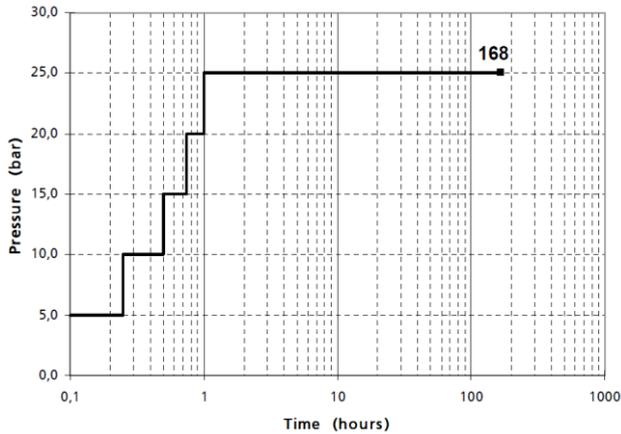


Figure 5 – Crack bridging test under 25 bar carried out for Gibe III dam (Ethiopia)

Puncture resistance under a hydrostatic pressure of 25 bar was tested to simulate the condition of a sprayed-polyurea applied on an irregular surface. For this purpose, a 2.3 mm thick sample was laid on a surface with triangular protruding asperities 5 mm high. The sample was then placed inside a pressure chamber applying a positive pressure from 0 to 25 bar for a period of 7 days. At the end of the test no signs of damage or leakage were observed.

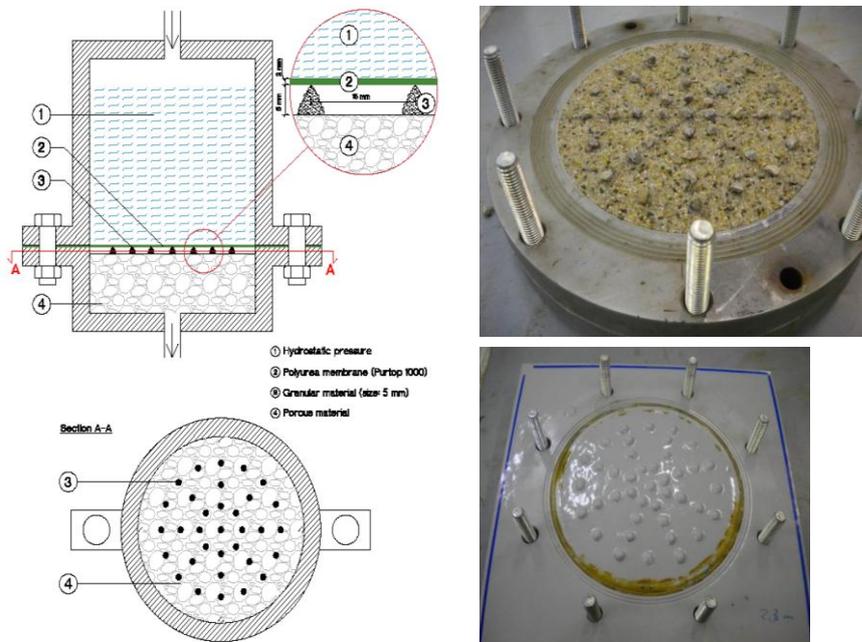


Figure 6 – Puncture resistance test under 25 bar carried out for Gibe III dam (Ethiopia)

In order to check the bonding performance on a substrate with characteristics comparable to those of the RCC facing and to identify most effective cleaning and surface preparation procedures, a 7 m long and 1.5 m high test-wall was purposely realized in Mapei laboratory and, other tests were subsequently carried out in Gibe III site.

Most promising procedure consisted of hydro-jetting (> 200 bar) of the RCC surface and subsequent application of two coats of epoxy-cementitious primer (with a consumption of about

600 g/m<sup>2</sup> per coat) loaded with quartz-sand at 50% by weight. The failure in pull-off test was consistently observed within the substrate, with an average value of 0.7 MPa.



Figure 7 – Pull-off tests under different support treatment procedures carried out for Gibe III dam (Ethiopia)

### 2.3 Gibe III, case study

Gibe III, located in the Southern Ethiopia Regional State, is the third plant of the Gibe-Omo cascade comprising Gilgel Gibe (200 MW) and Gibe II (420 MW), both in operation and Koysha (1800 MW) currently under construction.

The plant features a 250 m high RCC gravity dam, which is the world's highest of its kind and one of largest (6.2 Mm<sup>3</sup>), creating a reservoir with a length of about 150 km and a volume of about 15'000 Mm<sup>3</sup>. The project commenced in 2006, and impounding of reservoir started in early 2015, while the dam was still under completion, to bring forward the energy production. At the end of 2016-2017 rainy seasons the reservoir level reached about 90 % of the maximum head and at the end of 2020-2021 rainy season the reservoir reached the Full Supply Level.



Figure 8 – Gibe III dam, general view October 2017

Given the high and characteristics of the dam, the design of impervious upstream face was one of the key technical challenges of the dam. The main features of this design are discussed in Pietrangeli (2015).

The project is characterized by the presence of two middle level outlets in the dam body at el. 750 m a.s.l. (*i.e.*, about 100 m above the dam foundation level) but no bottom outlets. Therefore, the lowest portion of the dam is permanently submerged. An extensive large-scale investigation program was implemented to identify possible defective zones through the upstream face. This program included systematic water-tests of the drainage holes, drilled from one inspection gallery to another, while proceeding with the construction of the dam. Based on “permeability mapping” of the upstream face, specific protection works were designed and implemented, including epoxy

resins grouting, honeycombs repair, external waterstops, etc. In addition, as an additional line of defence, a 4 mm thick sprayed-polyurea coating was applied in the lowest portion of the dam.

The sprayed-polyurea overlapped with an external free-to-deform elastomer previously installed in correspondence of dam contraction joints (already protected by two internal neoprene waterstop and a drainpipe in between) thereby creating a continuous 4 mm thick impervious coating.

During the application of the spray-membrane the homogeneity of its thickness was checked by cutting-out inspection patches, using depth gauges, and by checking material consumption.

Leakage trends over time, collected from dam body drains spaced at 3 m in different dam galleries vertically spaced at 40 m, are illustrated in the graph below. It is noted that, in the lower galleries protected by the sprayed membrane, leakage rates have remained negligible over time, despite the higher hydraulic head and regardless of reservoir level fluctuations. Conversely, an increase of leakage flows over time has been observed in the drains associated with the contraction joints and in the portions of dam galleries extending into rock abutments.

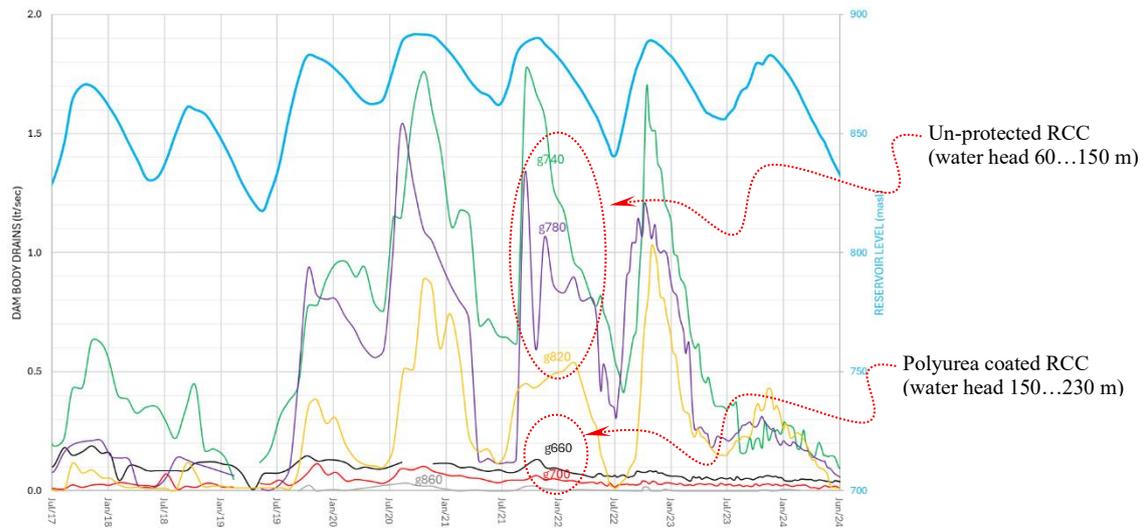


Figure 9 – Gibe III, total leakages from dam body drains at different dam galleries (data from EEP)

## 2.4 Conclusions

When correctly applied the spray-applied polyurea membranes provide a fully bonded, seamless, and impervious coating. As there are no gaps between the sprayed membrane and the substrate, and no joints within the membrane or at the membrane-substrate interface, any localized defect or damage occurring during construction or operation does not compromise the overall permeability of the system. Combined with its high elongation and crack bridging capacity, the spray-applied polyurea membrane is therefore capable of significantly improving the global watertightness of RCC dam faces, reducing the probability of leakages across possible localized defects, particularly in the joints between lifts, and contributing to the long-term structural performance of the dam.

The Gibe III experience demonstrates that sprayed polyurea, when combined with rigorous surface preparation, quality control during installation, and integration with existing joint sealing systems, can ensure durable watertightness. Monitoring data collected over several years confirm negligible leakage in dam zones protected by the sprayed membrane, despite high reservoir levels and reservoir fluctuations.

Spray-applied polyurea membranes therefore represent an effective complementary solution for enhancing the long-term hydraulic performance of RCC dams, particularly for high structures and permanently submerged zones.

However, due to the critical influence of site conditions (i.e. weather, substrate properties, installation procedures) on spray-applied polyurea performance it is necessary to plan a comprehensive site and laboratory investigation program, tailored to project needs, to ensure consistent performances. Standard qualification tests alone, in fact, may not be fully representative of actual conditions.

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