

Complex Infrastructure Systems Analysis and Management a Case-Study.

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ABSTRACT

Motivation

Complex infrastructure systems are difficult to model. Data is often missing or erroneous, changes are not well documented, and processes are not well understood, on top of it, under complexity, stalwart analytical tools have limited predictive power. The aleatoric risk, such as rain and risk cascading from interconnected infrastructures, is unpredictable. Mitigation, response, and recovery efforts are adversely affected.

methodology

In this research, complexity, nonlinear noncontinuous effects and aleatoric and data unknowns, are bypassed by directly addressing systems' response. Graph theory, statistics, as well as Digital Signal Processing tools are applied within a theoretical framework of the theory of faults [TOF].

Findings

A case of a complex infrastructure system is studied. Faults' virtual network is generated, statistics, spatio-temporal behavior and traits are produced. The gained understanding is compared to the physical system's design and to its modus operandi. Implications for design and maintenance are inferred, and DSP tools to manage the system in real time are developed.

Originality/value

The contribution of this research is in the provision of an explicatory theory and a management paradigm for complex systems.

KEY WORDS

Climate Change, Complex Infrastructure Management, Fault Risk, Stormwater Drainage Systems, the Theory of Faults [ToF].

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INTRODUCTION

Combined sewage and drainage system are cornerstones of civilization, in cities they are Critical Infrastructure [CI]. The roman Cloaca Maxima sewage and drainage system was considered “works for which the new splendor of these days has scarcely been able to produce a match” (Livius, AD17). There have been many changes to the practice since the time of the Romans, most notably, the development of rational models. These models which dictate design, are not a one-to-one procedure, but rather they provide various outcomes directed by policies such as sustainability, efficiency, and cost (Aronica & Lanza, 2005). There are well established means to deal with drainage design, maintenance, and operation, which may be presented as three sub-disciplines: capacity design, such as conduit capacity, source control such as delaying, ponding, infiltration, and system management, such as volume reduction by intelligent control (Yu et al., 2017). Computerized analysis enables the incorporation of ever-growing number of influential factors and their integration into correlated systems models such as in GIS based threat analysis (Mugume et al., 2015). EU legislative Directive 2000/60/EC for water management directs the coordination of multiple environmental systems into water management such as energy, transport, agriculture, fisheries, regional policy, and tourism with special emphasis on pollutants (Fontaine, 2000). Linked systems cause cascading disruptions in other systems such as power grids, sewerage systems, and roads (Apan & McDougall, 2015). Infrastructure systems are Complex [Complex Infrastructure Systems- CIS] (Yu et al., 2017). The meaning of “complexity” differs from the literal meaning of being “complicated”. It is a mathematical state that has specific traits and features. These features produce nonlinear system responses such as the butterfly effect that is the effect of small changes that cause large consequences. Aronica & Lanza (2005) studied a case of micro-topography effects of inlets that cause repetitive system collapses. There is a gap in the understanding of hydraulic drainage systems’ failures in general, let alone under complexity (Zhou et al., 2004). Aronica & Lanza (2005) suggest that there are many tools that may compete for this gap, if only the flow could be produced. This statement may seem odd when one considers models designed for this purpose such as the US Environmental Protection Agency Storm Water Management Model (SWMM) (Gironás et al., 2010). Aronica & Lanza (2005) explains that assessing flow for a complex topography is impossible and therefore modeling is impaired, this predicament is aggravated when considering that morphology is but one factor, flow is affected by a plethora of complex factors such as climate change (Jung et al., 2015), the statistics of deterioration (Salman, 2010) and social factors (Araya & Vasquez, 2022).

Is a working paradigm under complexity feasible? This article suggests the affirmative.

Complexity effects render non-complex design and forecasting tools inefficient (Mullapudi et al., 2017). Under complexity, linear models prove futile because systems response is not linear, finite elements solution produce outcomes such as the Lorentz attractors even for deterministic continuous systems with known initial conditions, let alone where systemic and aleatoric factors are stochastic. Under these conditions, simulations are usually prone to modeling mistakes and calibration bias (Mourad et al., 2006), because the processes are not Markovian in any order and emergent traits are changing the systems’ overall modus operandi; likewise, recursively adjusting systems fail because of the effects of a huge amount of small magnitude events and a small number of big magnitude events; and predictive control (Kändler et al., 2022) succumbs to the butterfly effect and to the disruptive effects of avalanche. Mullapudi et al. (2017) subjects the creation of future scenarios advocated by (Duan et al., 2019), based on a spatio-temporal explicit presentation promoted by Valizadeh et al. (2019) or a Bayesian belief network (Kabir et al., 2018), or on risk analysis (Johansson & Hassel, 2010), to a much-needed theoretical framework. Such theoretical framework

must be based on a concise paradigm that has an explicatory capacity and may be implemented to direct an application of tools to decipher CIS response, correct their design, and manage them in real time.

Addressing these needs is the aim of this research.

All effects and factors that penetrate the system, such as aleatoric risk and risk imported from other systems, cause a response of the system. This response is specific to the system, it forms a behavioral spatio-temporal map of the system. Faults are a manifestation of the systemic morphology and risk; their statistics is a trait of the specific system. By analysis of faults, it is possible to generate the system response without knowing the exact morphology, pathogens, and the rain spatio-temporal expression. This idea is not new. Mourad et al. (2006) analyzed a system as a black box, given all incoming effects and having gauges that produce all outcome of the system's single outlet, from effluence to BOD, formulating an almost one-to-one function response, his calculation of the retention tank was a straightforward good practice application.

From systems response, systems modus operandi may be produced, and corrective and remedial actions may be generated.

A factor that effects modeling viability is morphological data scarcity and its credibility. Assumptions made upon design become obsolete owing to system morphology changes, coverage changes, permeability factor changes, and climate change (Fitobór et al., 2022). This gap is addressed here using system Faults and hydrology data-banks.

In this article we use a case-study of a municipal drainage system to present a scale-free morphology, a complex aleatoric risk and a complex system response. Combined they form a Meta complexity. The mathematics that emanates not only suggests the ubiquity of the outcome, but its inevitability. Tools for forecasting and for reevaluation of design and tools to support the development of real-time management are presented.

The Theory of Faults [ToF (Yonat & Shohet, 2022b)] is the paradigm for complexity used here.

The layout of this article is: Following the introduction, Definitions and Concepts section relies specific meaning to some common concepts used here, followed by the research Method and Hypothesis. Next, in the Results section, the presentation continues along Figure 1 trajectory from PDF to Power function through descriptive statistics and DSP analysis to a generation of faults networks and the application of those to the physical realities of the case. Derived are morphology spatio-temporal maps, complexity effects, synchronization, attractors, and eventually DSP controllers. The Discussion and Summary section follows with further insights and inferences. The Conclusion recaps the findings, and the contribution of this article. The numerical data, morphology, statistics, explicatory parameters, morphology, attractors and PID are documented in the Appendix.

DEFINITIONS and CONCEPTS

Nodes -[here] Conduits in the physical system, faults in the information network.

Edges -link between nodes, here edge portrays timeline and WBS.

Rank - the number of nondirected edges emanating from a node.

Degree - the number of edges connecting a node.

WBS/Tree - **W**ork **B**reakdown **S**tructure the breakdown of a conduit to its supply lines.

Adjacency matrix connectivity matrix weighted by physical parameters such as capacity.

Viability Kernel

$$x(t) \in K \quad (1)$$

$$\dot{x}(t) \in F(x_i(t)) \quad (2)$$

Here $x(t)$ is state variable [route vector], $x_i(t)$ are the stage variables $F(x_i(t))$ is the decision function.

Attractors are paths that the system tends to prefer. Attractors act as minimum/maximum energy states that a net prefers under the excitation of a fault wave. PCA analysis shows that attractor are not paths but rather nodes (Yonat & Shohet, 2022a).

Hub -nodes with a high betweenness centrality.

Risk -[here] refers to Faults Probability Distribution Function [PDF].

Aleatoric Risk Generators -such as [here] rain.

Complex morphology -when nodes' rank has a power function and small world effects emerge.

Synchronization -In network analysis a loop is considered synchronized.

Avalanche: -when a local effect progresses the system to infinity [here to its edges].

The Butterfly Effect -when small perturbations cause unlimited effects.

Digital Signal Processing -[DSP] digital=numeric. Tools for system analysis and management.

Theory of Faults

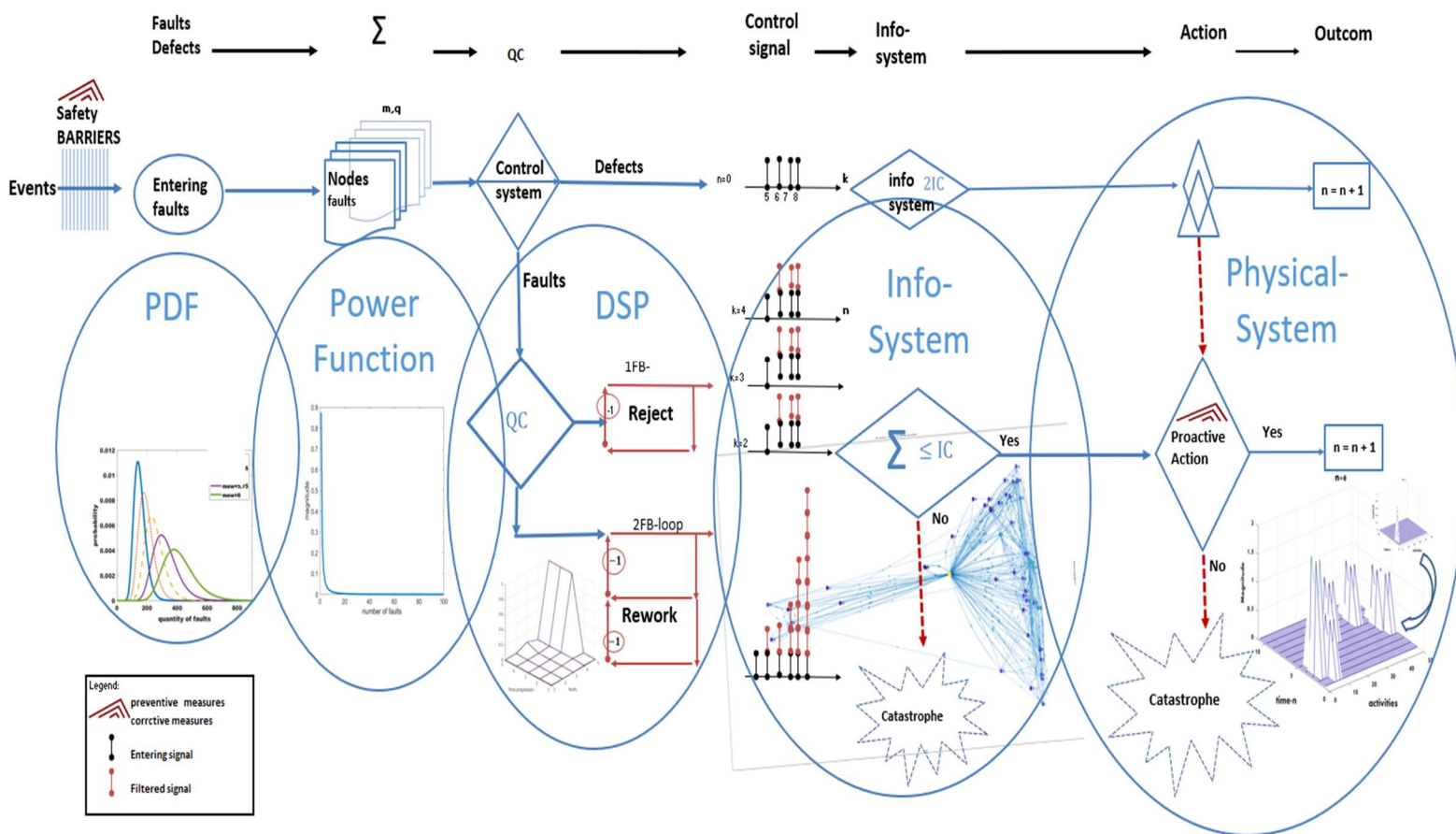


Figure 1. Graphical abstract of Fault propagation through the system

System response [here] to flows. The response is a product of the system's morphology.

Barriers protect systems from failure (Reason, 1995). such as standards for materials, praxis for workmanship, specs for suppliers, peer review for design, timely maintenance, and regulations,-prevent aleatoric risk translation to fault by weeding out causes of pathogens and by removal of pathogens.

Pathogens -clogging, sagging, air pockets, inlet capacity, hydraulic shock, background concentration, etc. Pathogens are caused by aging, inadequate materials, bad workmanship, latent design errors, etc. (Reason, 2000) pathogens are largely unknown.

Faults here are reported events related to drainage such as sagging, flooding, cover lifting etc. Fault may be generated by bad workmanship, materials deficiency, design mistakes, municipality maintenance actions and omissions, and so on. Faults may generate responses in the info-system. Once barriers are penetrated, the info-system has its chance to stem the faults at inception, otherwise, faults magnify, multiply and propagate to avalanche.

Faults PDF is log-normal (Horvath, 1959). The aleatoric risks are translated by the system to fault PDF.

Faults magnitude has a power function (Yonat & Shohet, 2022b).

Power function is generated by the log-normal PDF (Yonat & Shohet, 2022b), it is scale free; therefore, the same effects and outcome are manifested at each scale.

METHOD

The article employs an empirical approach (Johansson & Hassel, 2010).

A case-study of a municipal drainage system is studied.

Rain depth data is analyzed for the duration that matches the case-study data. The **Rain depth PDF** is generated and analyzed. **Faults PDF** is generated, **Faults' magnitude Power Function** is produced. **Fault** spatio-temporal **network** is developed. It is compared to the physical systems parameters, such as topography, roads, conduits. The physical system is analyzed by various tools of **descriptive statistics** and by DSP tools. The understanding is used to produce intake for design and design corrections, and to develop **DSP controllers** to automatically manage the system.

RESEARCH HYPOTHESIS

Physical infrastructure systems are a product of higher order information systems.

RESULTS

Rain Depth Characteristics

Daily rain thickness timeline data [Figure 2] indicate that the municipal stormwater drainage system master plan design assumption of smooth concave stratified rain functions [Figure 10.6] is irrelevant. The same erratic non-smooth behavior was found on the spatial axis too [Figure 7]. The meteorological station located but a few km away, produced data that was applicable for decades, no longer represent the rainfall of the studied municipality [Figure 7].

Figure 2 lays out a 7-year aggregated rain-thickness Histogram, a PDF fitted by Matlab statistics app., a rain-thickness time-line graph, and a rain frequency/amplitude graph generated by Fast Fourier Transform [FFT]. The Histogram shows that entire depth sections are missing, for example, within 7 years there - of 80 mm thickness. The rain thickness fitted PDF is non-parametric [Figure 2.2]. There is roughly the same probability for 20- and 40-mm events and a 350 mm event. Events of 350 mm have not been recorded yet, but above 100 mm events have become a probable occurrence, much like a 50 mm events. The 7-year daily rain graphs presented on shared ordinate scale of ordered ordinate, show a chaotic pattern [Figure 2.3]. The FFT is a manifestation of complexity [Figure 2.4]. There

is a similar probability for different frequencies. This is a falsification of the [Figure 10.6] concave rain-depth probability paradigm.

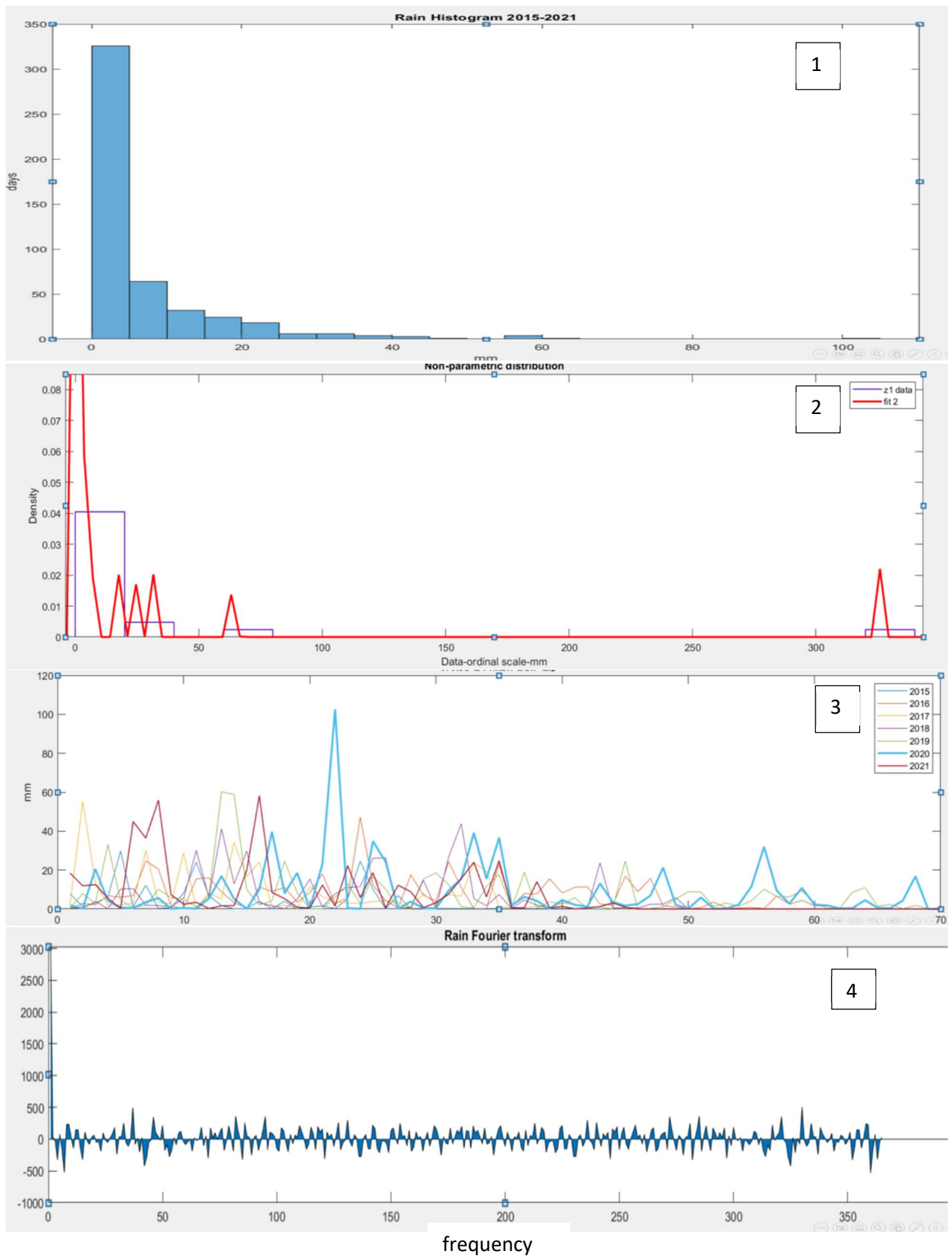


Figure 2. Rain attributes by 1.rain histogram in mm, 2.rain PDF, 3.rain scatter plot, 4-rain FFT

Fault Statistics

The municipality report center notes all incoming complaints, sorts them by discipline, weeds-out redundancies and sends a professional to verify each report. The Appendix archives verified stormwater drainage system related reports on [Figure 8](#). The data log documents about 22,700 verified drainage related reports acquired in less than 7 years. The sheer amount is an indication to avalanche. The data supplied by the report center was sorted by the center according to 4 fields: Date-Time of opening a complaint, Date-Time of closing a complaint, location, and nature of fault. Per the data, there are no open faults, ostensibly every known “pathogen” is meticulously weeded out. Active pathogens are latent.

The physical system hydrologic parameters were taken from the master plan hydrological data [Figure 9], this data is partial and based on assumptions [such as coefficient of imperviousness, conduit fill rate, Kirpich coefficient etc.]. Some hydrological considerations [Figure 10] were taken from the master plan to show that the system is by no means capable of draining the city, even in case of the design storm. Some spatio-temporal descriptive statistics is presented on [Figure 11](#). Timeline Histogram shows a probable avalanche in 2019 that permanently altered the system’s response. Street flooding percentage of total expectancy [Figure 11.3] points towards possible attractors, and the Pareto diagram of streets faults’ expectancy [Figure 7Figure 11.4], shows that 10% of the roads sustain more than 60% of the faults, while 20% of the roads are a locus of about 90% of the documented faults.

Fault PDF is presented on Figure 3. Lognormal PDF was found to have a good match, as provisioned by the literature (Horvath, 1959), and experience (Yonat & Shohet, 2022b).

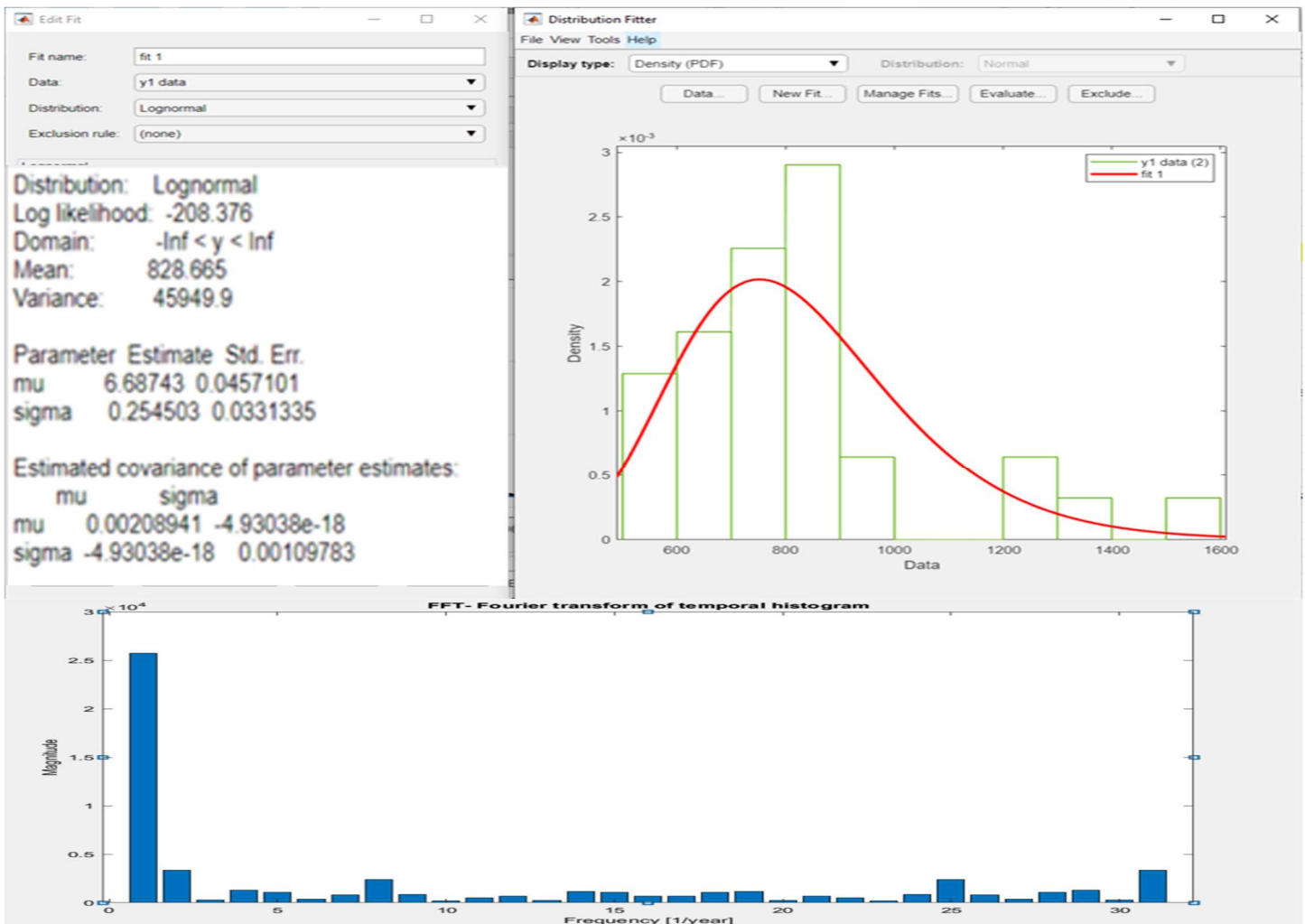


Figure 3. Matlab generated 95% confidence interval faults PDF and FFT

The PDF was generated by Matlab statistic app. For 95% confidence interval.

The FFT of the Faults log shows repetitive formations consistently covering the whole ordinate [Figure 3.2].

Curve fitting Matlab app. found power function $[a \cdot x^{-b} + c]$ to be the best fit [95% confidence interval, $R^2=0.96$] for representing the magnitude of the faults [Figure 4].

$Abs(b)=0.4$ complies with avalanched projects and infrastructure facilities.

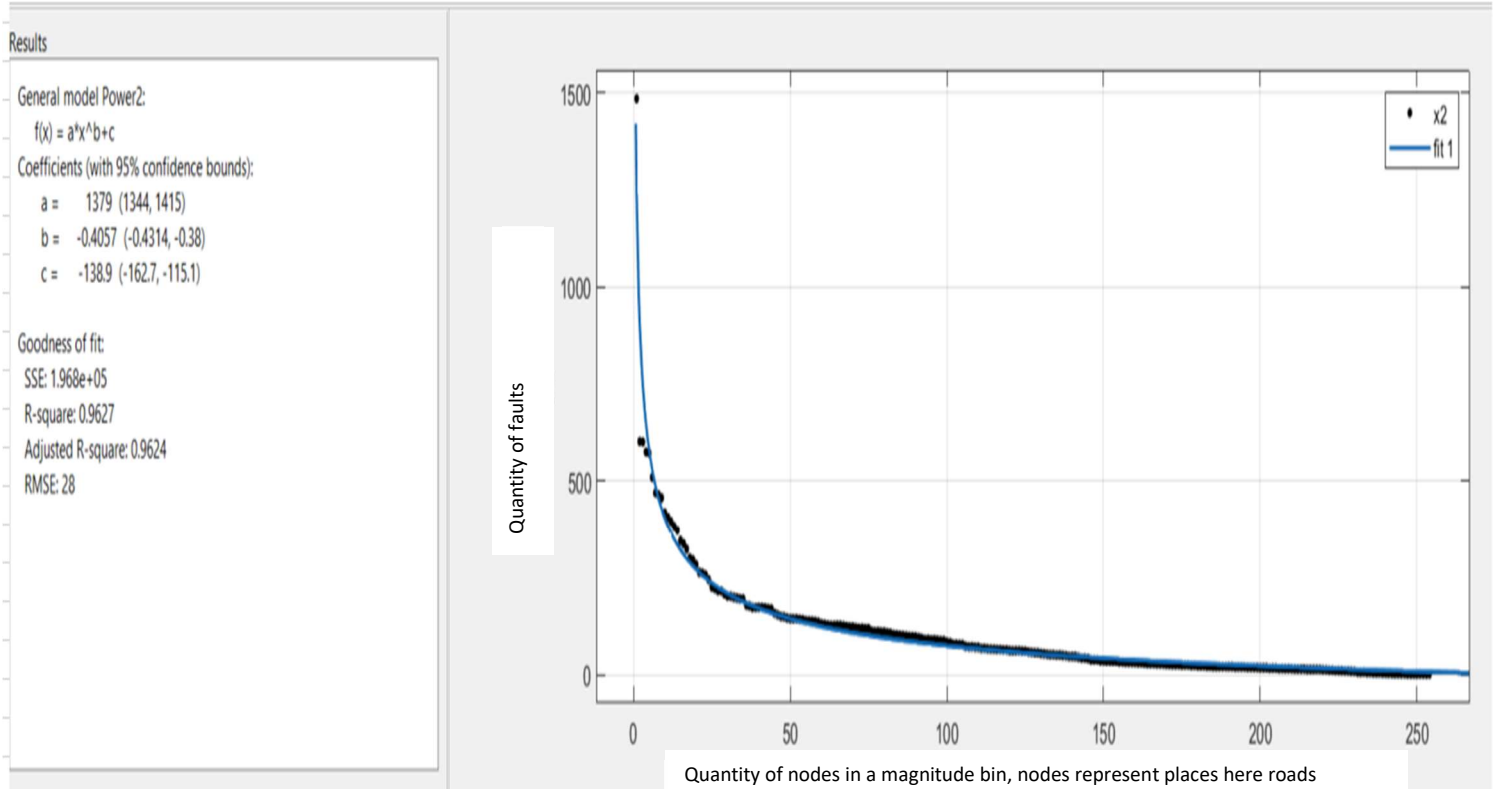


Figure 4. Power function fitted by Matlab app.

The power function exhibits a trait of constant “noise”. This noise is called “White” when its attributes are not correlated with those of the magnitude of faults. White noise can be random, or it may have a repetitive trend. The origins of the white noise were investigated and traced to an avalanche in the sewage system in 2018. This sewage system fault was correlated on Figure 15 with an avalanche in the drainage system a year later, causing a permanent effect. Power functions are formed in almost any spatial analysis such as on Figure 16.4 which is a spatial presentation of one specific fault, and on Figure 11.3 for the aggregation of all faults.

Figure 5 shows that the stormwater system is flooded also in the summer when there are no rains. The initial supposition that it is flooded by wash water deposited by summer pumps was rejected because the complaint log clearly indicated sewer. The deposition of sewer into drainage systems is illegal in Israel, perhaps that is why failures cascading between these infrastructures were not considered and patterns related to its correlated failures caused by interdependencies were neglected.

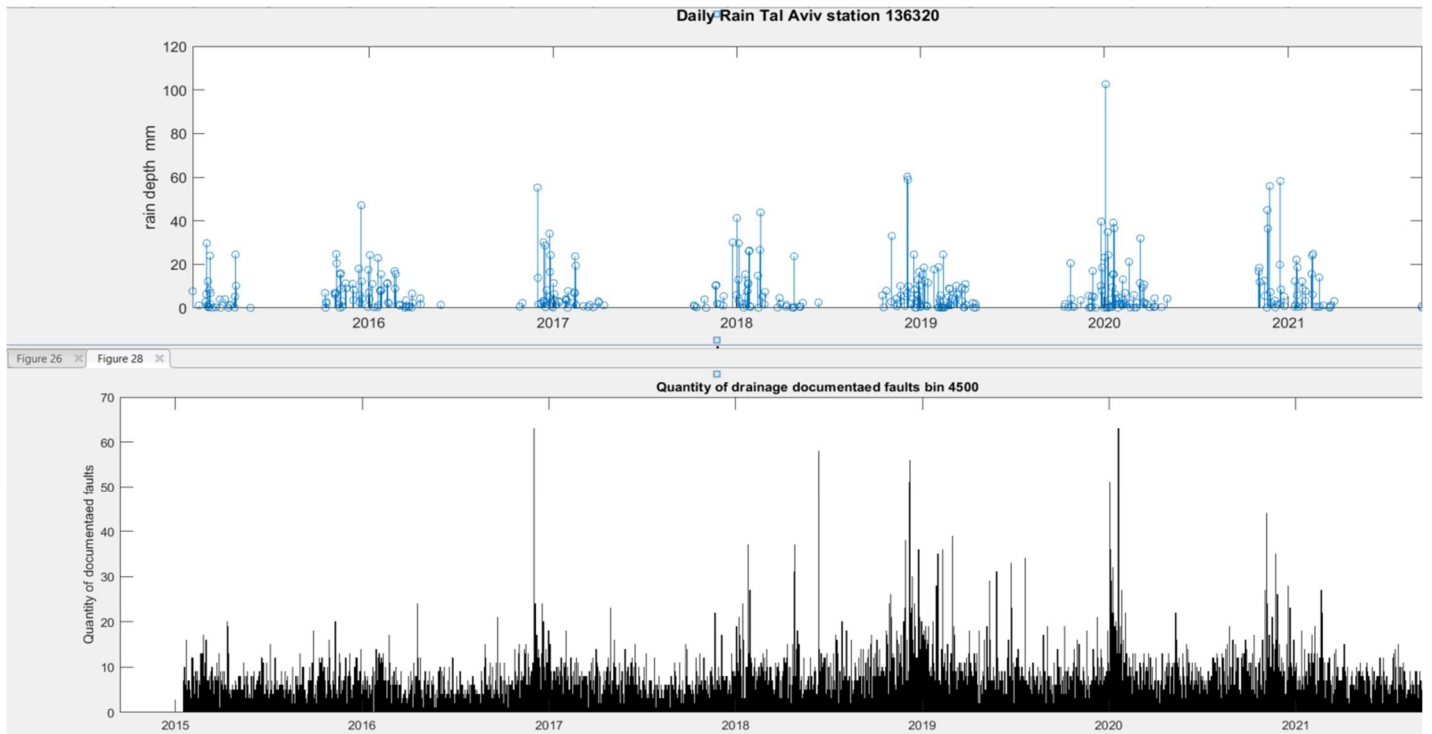


Figure 5. Rain timeline vs. flooding timeline. Histogram accumulated for 10 hour spans.

System Morphology

The municipality occupies an 8 sq.km watershed adjacent to the Mediterranean Sea. The general topographic inclination is towards the sea, to where the western outlets are directed. There are three main catchments: East, N. West and S. West.

The municipal drainage system is a Critical Infrastructure, affecting service, cost and on rare occasions causing loss of lives. There are cross effects with other infrastructure systems, in this case-study with the sewerage and road systems [Figure 15].

There is only partial data about the physical system, even this data is rendered irrelevant because the planned and executed system is modified, clogged, sagged, conduits are fractured, their gradient changed, there are illegal addition especially of sewage connections and relentless densification caused changes in the coverage and permeability factor.

Aleatoric events that penetrate the barriers become Faults.

Faults create virtual networks [Figure 6, Figure 18, Figure 19]. These networks are spatio-temporal. The plots were generated by Matlab from faults adjacency matrices.

The nodes are faults, the edges are propagation trajectories. The scale can be enlarged to view a specific rainstorm such as on Figure 6, or zoomed out to show the system general morphology such as on Figure 18.

It is evident [Figure 18] that the system consists of Hubs, it has subgraphs with modular repetitive hierarchies, and there are incidents of coupling. It is important to weigh the network against the viability kernel, to evaluate edges that may present a queue in the complaint center rather than ones in the drainage system.

The western parts of the system have only two outlets [Figure 18]. The calculated capacity of those outlets (Figure 10), gives us a gross estimate of the total capacity of the system. Total catchment area for the N. Western outlet is calculated in Figure 10.4 for a rain of the designed concentration time and total volume [Figure 10.1]. The calculation assuming the system averages on one outlet for that catchment yields a time for clearance that is at least on order of magnitude bigger than the actual one [Figure 10.1], thus falsifying the assumption that the drainage system drains the city.

Figure 6 presents a recurrent emergent trait of water flowing under pressure against the gradient, flooding uphill locations. In this case water travelled 8 km upstream flooding the areas along route. The white dashed arrow on Figure 6.2 shows the farthest reach of the phenomenon, which is the farthest extremes of the net. This is an avalanche.

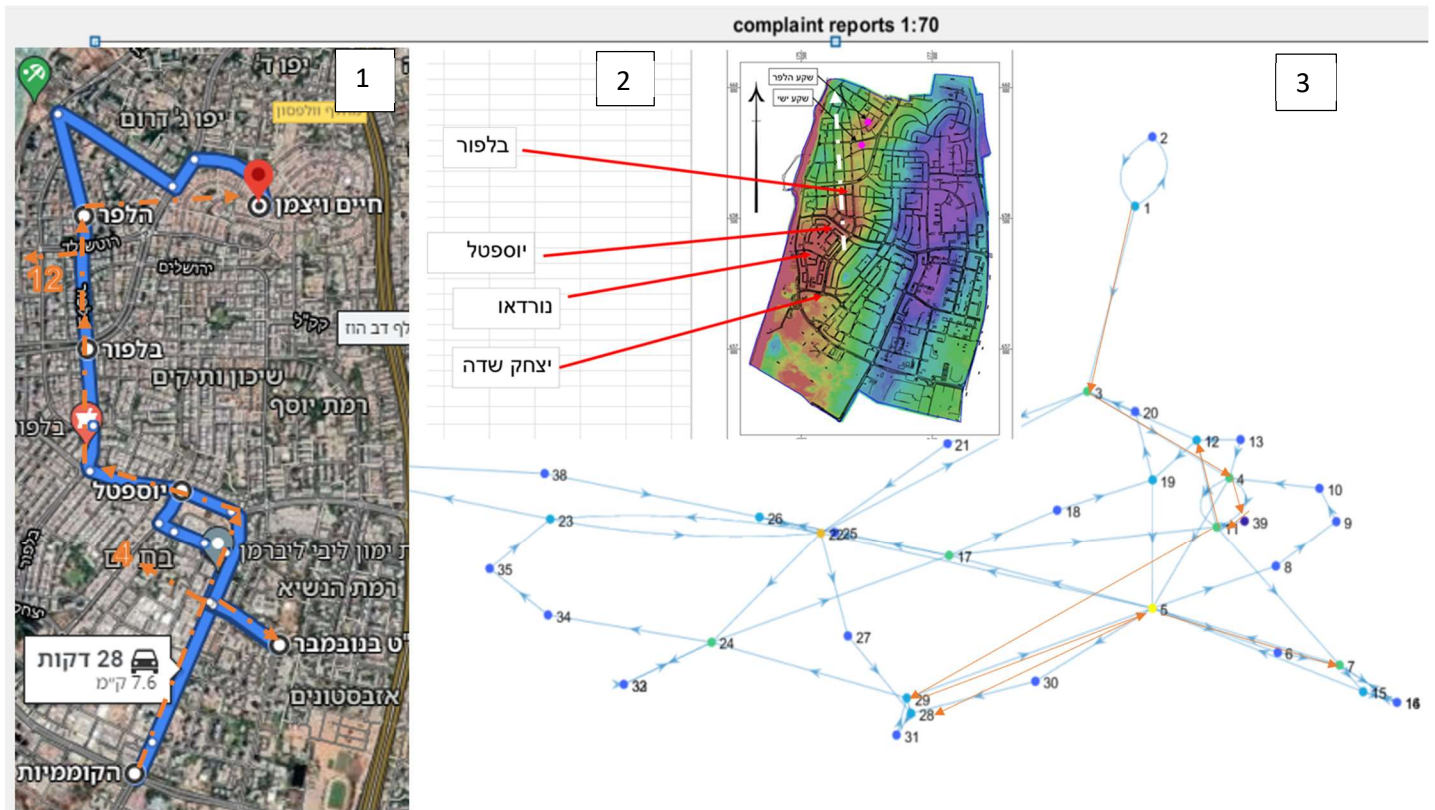


Figure 6. Partial virtual faults network (1) vs. physical conduits (2) and topography (3)

Node 1 on Figure 6.3 is the first [left most] on Figure 16.3. Whether this pressure vessel is the power engine of the pressure system or its outcome may be suggested from the fact that cover burst and pressure discharge do not change the trajectory of the pressure system, on the contrary, it precedes it. Figure 19 presents the role of a hub.

This hub generated a “black swan” event of flooding of the adjacent uphill catchment [colored in pink on the topographic map Figure 19.1]. This water main on the low catchment has a root in the adjacent uphill catchment (circled with a dashed line). Water velocity and pressure forced the pressurized transport of floodwater from the low adjacent catchment to the upper one. The explicatory model is presented on Figure 19.4. The pressure in the main is higher than that of the supply pipe, thus water in the supply line is stacked to the height of the water in the main, this stacking goes up the conduit according to the height pressure. Water that flows above that level can pour into the main. When water level in the main is above TL of the supply pipe, water flows under pressure to be siphoned out of manholes. We used the Bernoulli equation to calculate the pressures [Figure 16]. Air pockets in the sewage system are formed, hydraulic shocks, turbulence, hydraulic jumps all contribute to the chaotic response. Water streamed up the dashed vertical lines of Figure 19.3 in sequence, and only after filling the red dashed conduits, the uphill effect is created.

In the western part of the catchment presented on Figure 19.1, the land is flat and average gradient is 0.3% at most. The gradient of conduits is roughly the same. For the same effect to appear when invert level of the supply line is higher than that of the main, a flooded manhole and a main that is full and operate under pressure is needed [Figure 16 Figure 16.3 respectively].

This main conduit acts as an attractor, meaning that it is flooded in many instances. The flooding surfaces through gutters and manholes to the ground, in the same specific locations, which are the manifestation of that attractor. These attractors are expected to be flooded when different aleatoric events happen and different pathogens such as clogging or sagging of manholes are active in different places.

Loops are formed on a system level such as the grand loop leading to node 3 in Figure 19.2, and on a local level such as the coupling of nodes 31 and 67. These loops indicate higher topologies. A salient example is formed on the northern extreme of the main in Figure 19.3, where the two local recesses [Figure 13] are located [Figure 12 noted by a solid red line]. Here an emergence of a coupled tank system- an oscillator- is noted Figure 19.5.

DSP

Some DSP controllers were developed for sections of this case's physical system and for the management of the recesses. Perhaps the simplest most forward one is a PID controller suggested on Figure 20. The idea is to create a seasonal pond in the noted location, taking in the adjacent flows [represented by double blue arrows], thus relieving the system. The soil is sand, therefore there is a considerable infiltration [the parameters are noted on Figure 20]. All the flows are gravitational but one. The pump location is noted. The pump is needed because a block in the system is formed at this junction owing to a Bernoulli effect of velocity and pressure. The pump role is to over pump the main, thus, to reduce the pressure up the conduit and relieve the system further upstream. There is an overflow slide [noted in orange arrow], that is a safeguard for extreme events of flooding. The system works as a crude surge tank because the junction noted with a red ellipse on Figure 20 is blocked when the system is flooded, and backflows are directed to the pond.

The only sensor used is a water level gauge for the pond. This is in essence an integral indicator. Thus, the effect on the PID design parameters [Figure 21] is the almost nullifying of the Integral part of the PID controller.

The PID was developed in Matlab Simulink control system toolbox [Figure 21]. PID app. had to be limited to the capacity of the system and the pump. Water level gauges provide Integral, velocity may be a measure of Derivative while in other formations, flow may indicate the Proportional. In some cases, it is possible to substitute a DSP tool for a Feedback loop. An example for a simple feedback system: in section 14 of Figure 19.3, the pink rectangular dot represents a "summer" pump that pumps excess water into the local main which has a branch into the Halper [upper] recess. A controller may be added to close that branch by a valve when Halper height gauge indicates water level above a set height. This is a simple proportional management. This logic may yield sub-optimal solutions when the Halper pump capacity is sufficient to sustain the flows. A different approach is a feedback loop that returns the pressure against which the pump works. This approach is better because the main conduit flooding is a precursor of the recess flooding.

DISCUSSION and SUMMARY

CIS are produced by information systems, first because CIS are built according to design, next, CIS are operated and managed by information systems, and last, it is information that dictates CIS maintenance. This statement portrays the hypothesis as a tautology. CIS produces feed and feedback information that info-systems need to operate and maintain. CIS produced data exhibits systemic characteristics; system response is not random, it has the specific characteristics of the information system, a specific statistic, morphology, modes of response, attractors, and emergent behaviors. These systemic characteristics support the research hypothesis, enabling the suggestion of digital twins embedded in the info-system.

Owing to climate change, rain characteristic changed considerably relative to the municipal master plan database. Rain patterns are divergent spatially and temporally. It was found that rain behavior became erratic, non-continuous spatially [Figure 7] nor temporally [Figure 2]. The probability depth diagrams [Figure 2.2] are no longer ordered by expectancy [Figure 2.4], they are no longer concave [Figure 10.6] nor continuous [Figure 2.1]. These findings render the historical data and the stalwart design paradigm obsolete.

The physical system plans supporting the municipal drainage master plan [Figure 12] were proven lacking, erroneous at part, and in general not representing the actual physical system [Figure 18]. Further analysis attested to pathogens that were not treated, amounting to an avalanche and a loss of systemic teleonomic coherence [Figure 16]. The stalwart analytical tools used in the master plan were proven wrong, owing to morphology changes, interconnectivity with the sewerage and road systems, un-continuous flow in the drainage system (owing to phenomena such as bursts, air pockets, and of feeding to other systems), unaddressed complex modes of operation such as coupling and emergent traits such as pressure vessels.

In the case-study analyzed here, the municipal report center provided data [Appendix] that was the database for the recreation of the information system. It supplied a partial picture of the maintenance efforts captured by Date-time reports [Figure 9]. The documented enormity of faults recurrence is by itself a testament to the vain efforts of maintenance efforts [Figure 16.3].

Faults PDF was found to be lognormal. This finding is a manifestation of a general rule (Horvath, 1959) suggesting the machination of correlated faults. The Fast Fourier Transform of the Faults log [Figure 3.2] shows erratic behavior with repetitive formations.

The magnitude of faults was best fitted by a power function [Figure 4] as provisioned by ToF (Yonat & Shohet, 2022b). Power function is an indication of complexity. It implies a big quantity of small magnitude events and a small quantity of big magnitude events and a multitude of complex phenomena such as, the butterfly effect shown on Figure 5 where at the end of the 2018 rain season, a rain of 2.5 mm thickness caused an avalanche. Local power functions are aggregated by the complex system to super-power-function and super-power-function synchronize local power function behavior. This is manifested in correlation of faults, complex vibration, and propagation modes.

There were black swan phenomena such as the flooding portrayed on the ridge over the water divide line in the adjacent catchment basin [Figure 19.3]. There were emergent traits such as conduits acting as pressure vessels thus flooding upper regions [Figure 16.2], and the emergence of oscillators [Figure 19.5]. Figure 4 is a degree distribution, therefore indicating complex morphology, - scale-free network. Scale-free networks are an outcome of preferential attachment (Barabási & Albert, 1999), therefore a mandatory outcome of WBS morphologies. The formation of loops creates higher topologies that are transient [Figure 6.3], here- different loops may be produced on different occasions. The free element of the power function equation represents constant “noise”. It was shown that the noise is not “white noise” [Figure 14] as provisioned by the equation constant. It is only a product of the limitation of our data and analytic tools, the scale free function provides the same results at all scales. The magnitude of the noise showed repetitive formations befitting a recursive sub formations morphology. The origin of the noise was traced to a sagging of the sewage system that caused an unreversible damage to the drainage system [Figure 15].

The power functions spatial manifestation was a recurring finding. It was presented on Figure 16.4 for a spatial manifestation of a specific type of fault and by a Pareto diagram [Figure 11.3] for an aggregated function of all faults. The Pareto indicates that 90% of the faults recur in 20% of the locations. This attests to a phenomenon of attractors. Energy may be dissipated locally or accumulate to global effect. The deciding factor may be local, such as a clog, yet, most times, the outcome prefers an attractor. An attractor was studied [Figure 19], it generated upstream successive fluxes [Figure 19.3] and a “black swan”, of first time flooding a higher catchment. These effects were matched with an explanatory model [Figure 19.4]. The effects of complexity set limits on prediction. Attractors on

the other hand direct efforts to a Pareto efficiency. These effects are a product of design errors that might have been latent in the past, but now, having become active, “remedial” designs that offer to relieve the system by adding links to mains, would exacerbate the situation.

The power parameter b was found to be $b < 1$ which implies that the whole system is one giant cluster (Aiello et al., 2001). This directs an understanding that a local disturbance may avalanche through any part of the system and through the entire system.

The morphology shows repetitive structural formations and recursive sub formations. The morphology of the generated fault network is not similar to the physical morphology of the system [Figure 12]. The data about physical morphology was proved lacking. Markedly, there are no notations of crossovers with the sewerage system, manhole heights, and inlets invert levels. The Virtual fault networks bypassed all systemic unknowns, changes, modifications and imported risk and related directly to the system’s response. Fault networks suggested flows, directions, incorporated sewage, and roads, as well as flooding locations, identified attractors and highlighted hubs and emergent formations. Pathogens, such as manholes’ sagging, pressure vessels, air pockets, and many other products of maintenance deficiencies and design latent errors are hidden. In the case-study, descriptive statistics pinpointed a major event of sagging of the sewerage system, noted on Figure 15, that changed the gradients, caused incessant clogging and a loss of operational and teleonomic coherence in the drainage system. The virtual networks were compared to known physical data to derive an understanding and decipher the modus operandi of the actual system. It was found that the drainage system cannot drain the city within the timeline the city is drained, not even for the design rain thickness [Figure 10]. It was found that an alternative drainage system is formed, using roads’ gutters as conduits [Figure 16.1]. The system undergoes a phase transition from a drainage system to a syphoned conductive system that conveys effluents upstream.

DSP tools among many real time management tools are readily available. DSP tools were presented here for the management of the recesses and a for a suggested seasonal pond. It is paramount that the use of these tools is within a theoretical relevant model, in our case, - ToF. Whenever possible, simple low-tech solutions are advised. Simple mechanical low maintenance stand-alone contraptions are oftentimes better fitted to serve the systemic needs, such as a simple non-return mechanical valve to prevent the coupling effect of Figure 19.5.

The deciphering of the rain characteristics and the system Modus Operandi were put to immediate use in the commissioning of a municipal meteorologic station, submission of a revised drainage master plan, the stoppage of a pending counter productive investment, and the suggested use of DSP and feedback controllers.

CONCLUSIONS

This paper introduces the application of the **Theory of Faults** to analysis, design, management, and control of a CIS. It was suggested that the physical CIS is a part and product of an information system. A fault log was analyzed to produce the trajectories of faults that propagate the systems and cause disruptions and morphological changes. These trajectories were tracked on the info-system spatio-temporal networks. Local snapshots were presented. These spatio-temporal maps are the system’s response, they were generated without knowing the exact morphology, pathogens, and the rain depth spatio-temporal expression.

By comparing the virtual system to what is known of the physical one, design implication and real time management tools were developed and employed.

It was shown that complex systems may be evaluated and managed by analyzing system response. It was deduced that although the actual system morphology and pluvial flood risk are not known,

system attractors and emergent behaviors may be discerned, and design corrections and real time management tool may be developed.
 Similar tools with morphologically similar presentations and responses were developed with ToF methodology for power grids and for HVAC maintenance.

Grants

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⁴ Sagie J.A. engineering and Construction LTD

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APPENDIX

Rain

Spatial distribution

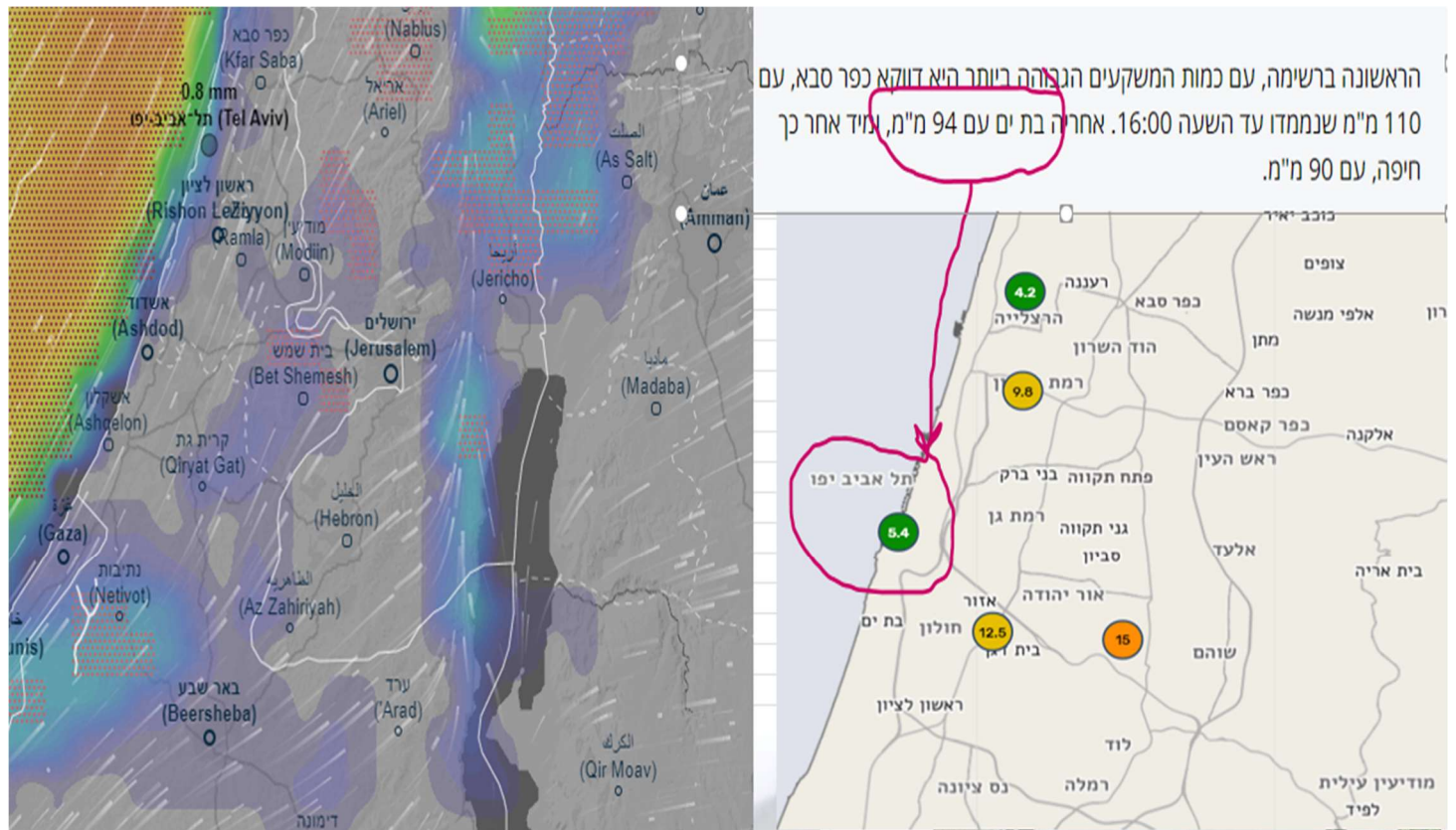


Figure 7 Rain spatial distribution for the 19.11.2021 rainstorm. The upper red circle denotes the local rain thickness, the lower one in the thickness in the barometric station.

Fault Log

11:30 02/11/2021	08:30 28/10/2021	חדש	80	החשמונאים	פעיל	קולטן מי גשם שבור סקר	קולטן מי גשם שבור סקר	CAS-988412-D6X4K2	25684
12:38 28/10/2021	09:38 28/10/2021	חדש	27	ביאלק	פעיל	מכסה ביוב התרחמם סקר	מכסה ביוב התרחמם סקר	CAS-988449-M4K6G3	25685
10:45 02/11/2021	09:45 28/10/2021	חדש	27	ביאלק	פעיל	שקיעת ריצוף ליד בריכת ביוב סקר	שקיעת ריצוף ליד בריכת ביוב סקר	CAS-988452-M9Z1T3	25686
11:09 02/11/2021	10:09 28/10/2021	חדש	29	שד' העצמאות (65-29)	פעיל	שקיעת ריצוף ליד בריכת ביוב סקר	שקיעת ריצוף ליד בריכת ביוב סקר	CAS-988461-M9X4Y2	25687
08:22 31/10/2021	11:21 28/10/2021	הבעיה נפתרה	9	דוד רמז	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988489-G5C4P6	25688
11:00 31/10/2021	14:32 28/10/2021	הבעיה נפתרה	92	יוספטל (זוגי 2-76)	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988564-T4Q7R1	25689
11:00 31/10/2021	16:10 28/10/2021	הבעיה נפתרה	10 - 12	השר פנקס	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988585-W5S7T8	25690
10:00 31/10/2021	09:02 29/10/2021	הבעיה נפתרה	1	בלפור (92-48)	נפתר	שקיעת ריצוף ליד בריכת ביוב סקר	שקיעת ריצוף ליד בריכת ביוב סקר	CAS-988711-N7T8	25697
11:00 31/10/2021	09:53 29/10/2021	הבעיה נפתרה	2	הרב ניסני	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988711-N7T8	25698
11:00 31/10/2021	10:17 29/10/2021	חדש	3	ליבסקינד	פעיל	שקיעת ריצוף ליד בריכת ביוב סקר	שקיעת ריצוף ליד בריכת ביוב סקר	CAS-988711-N7T8	25699
11:00 31/10/2021	10:57 29/10/2021	הבעיה נפתרה	11	השר שפירא	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988747-L4Y9X6	25700
11:00 31/10/2021	11:21 29/10/2021	הבעיה נפתרה	16	דניאל (זוגיים 14-82)	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988755-G0F126	25701
11:00 31/10/2021	13:30 29/10/2021	הבעיה נפתרה	73	ארלזורוב (5, 46-82)	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988779-V0K1S4	25702
11:00 31/10/2021	17:13 29/10/2021	הבעיה נפתרה	33	יוספטל (זוגי 2-76)	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988802-K4C9Y4	25703
11:00 31/10/2021	14:50 30/10/2021	הבעיה נפתרה	120	בלפור (154-94, 165-120)	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988865-N9B0M2	25704
11:00 31/10/2021	17:08 30/10/2021	הבעיה נפתרה	6	קדושי קהיר	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988870-Q6P8S1	25705
11:00 31/10/2021	18:51 30/10/2021	הבעיה נפתרה	45	בלפור (105, 48-92)	נפתר	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988877-P6W3W1	25706
07:13 03/11/2021	07:12 31/10/2021	חדש	82	הרצל (זוגיים 2-48)	פעיל	קולטן מי גשם סתום סקר	קולטן מי גשם סתום סקר	CAS-988919-X8Q6C7	25707
08:02 03/11/2021	08:02 31/10/2021	חדש	5	הנביאים (אי זוגי 5-77)	פעיל	שקיעת ריצוף ליד בריכת ביוב סקר	שקיעת ריצוף ליד בריכת ביוב סקר	CAS-988939-D2T0J5	25708
13:00 31/10/2021	09:00 31/10/2021	חדש	19	הנרייטה סולד	פעיל	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-988984-R5T6H7	25709
13:23 31/10/2021	09:23 31/10/2021	חדש	128	בלפור (105, 48-92)	פעיל	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-989000-F9X0M1	25710
13:24 31/10/2021	09:24 31/10/2021	חדש	7	דקר	פעיל	סתירת/ הצפת ביוב סקר	סתירת/ הצפת ביוב סקר	CAS-989001-G7X5W2	25711

Figure 8. Faults log-Date/Time of opening of report, Date/Time of closing, place, category

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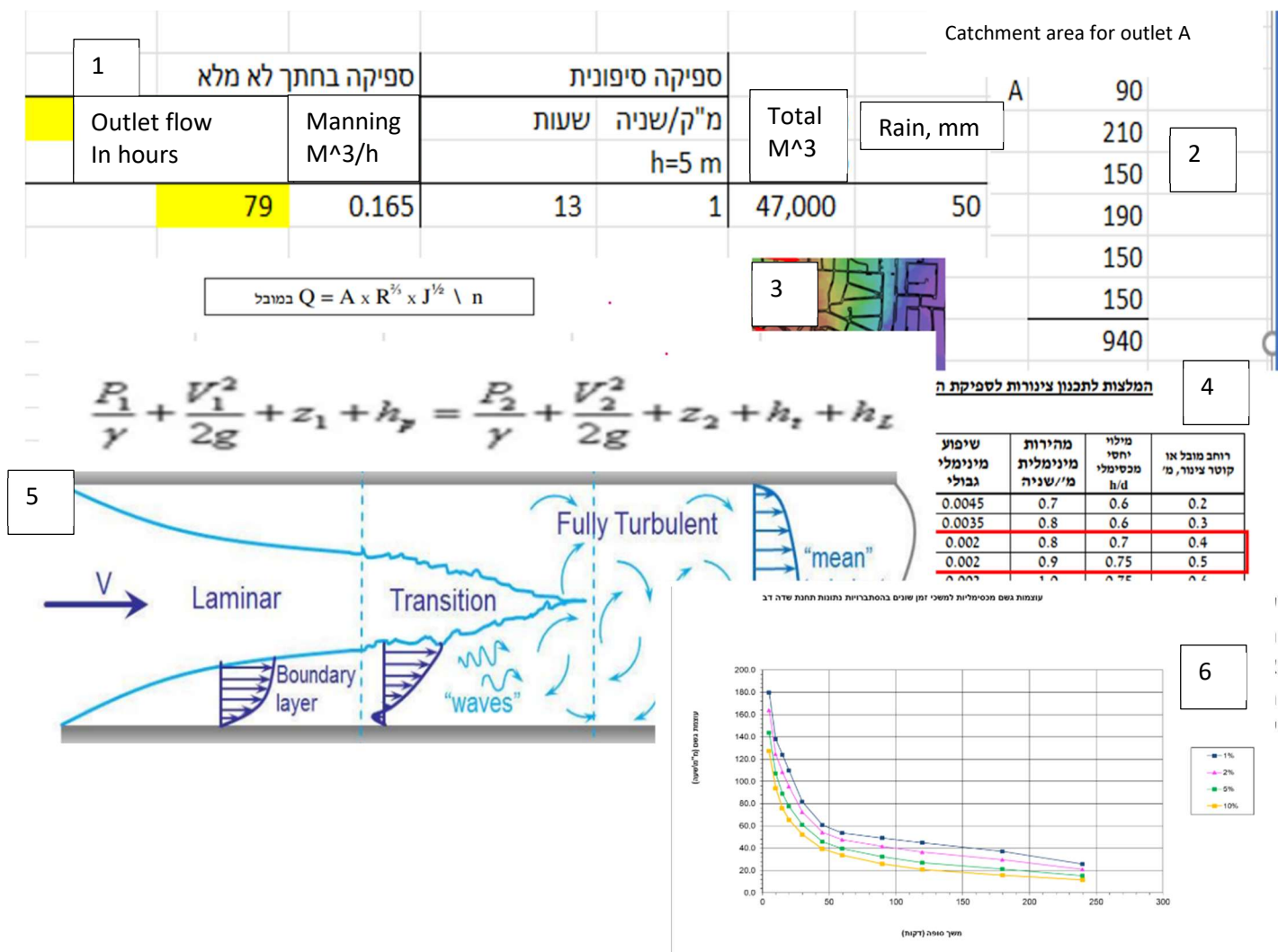


Figure 10. Hydrological considerations based on Manning and Bernoulli and Kirpich equations enables a gross estimate of the total capacity of the stormwater system capitalizing on the fact that there is only one outlet for the western sub-systems.

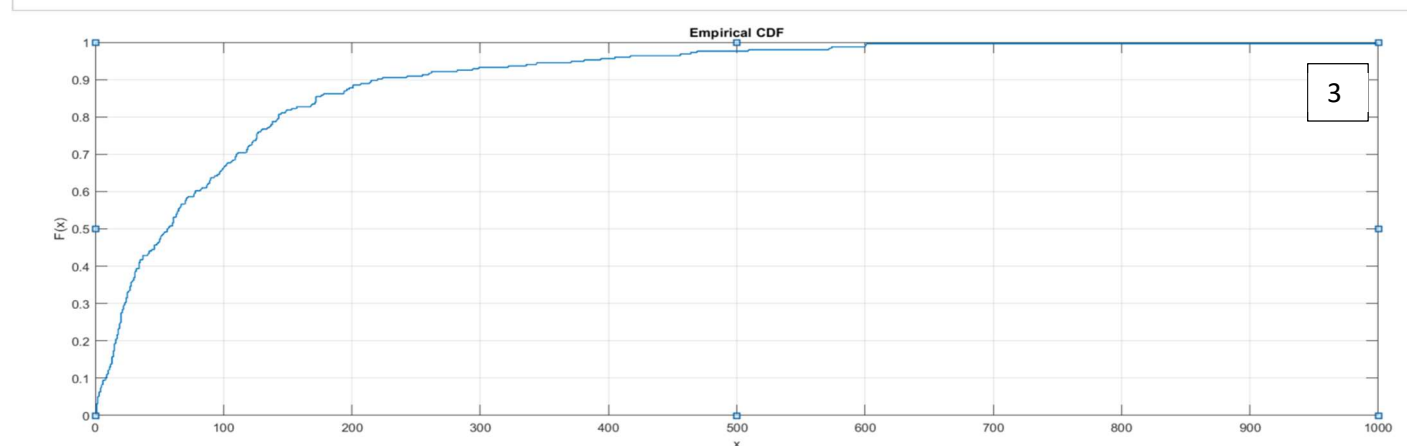
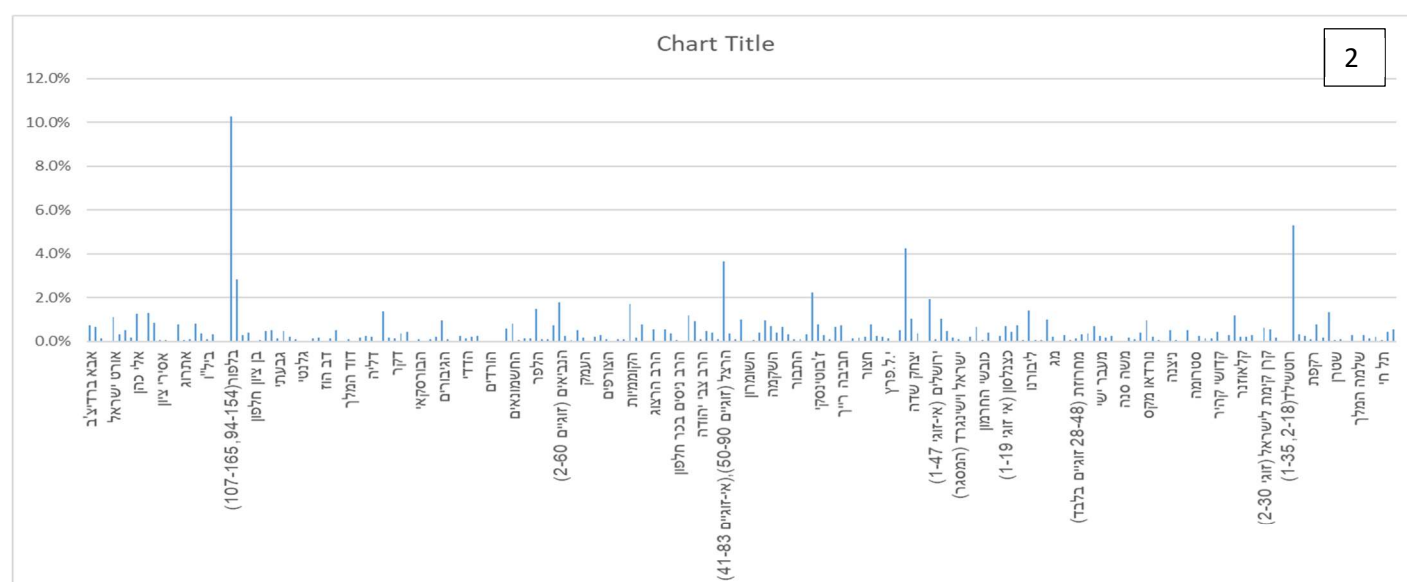
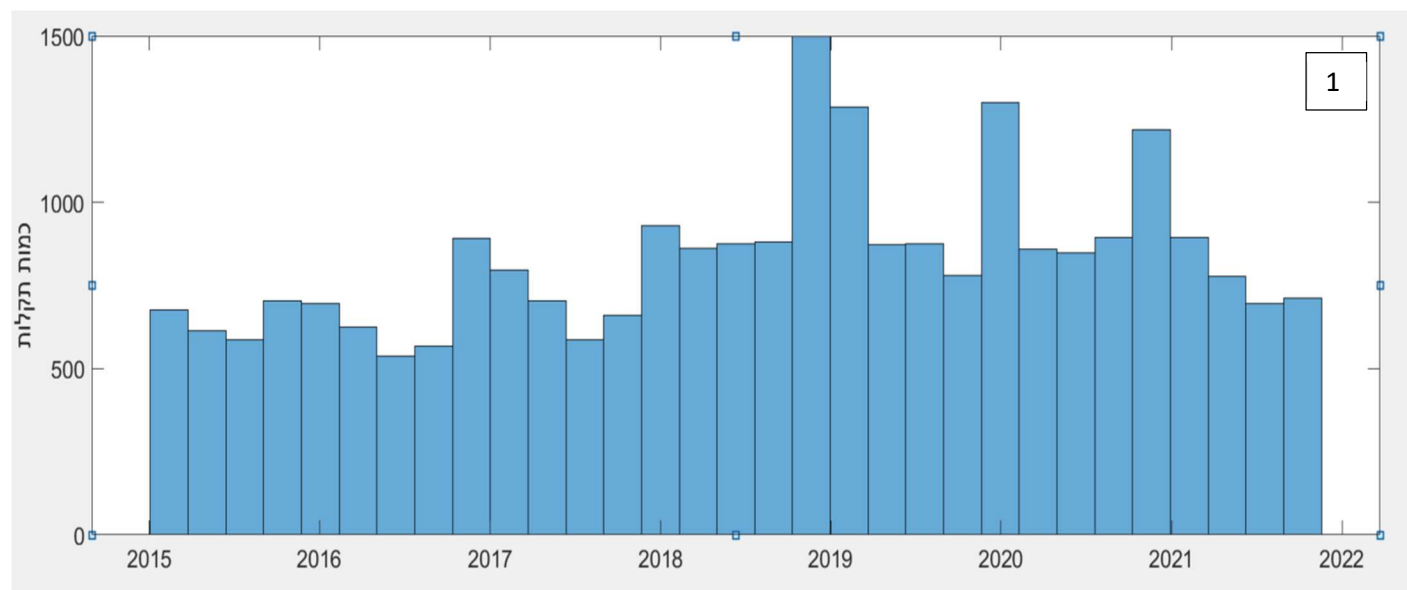
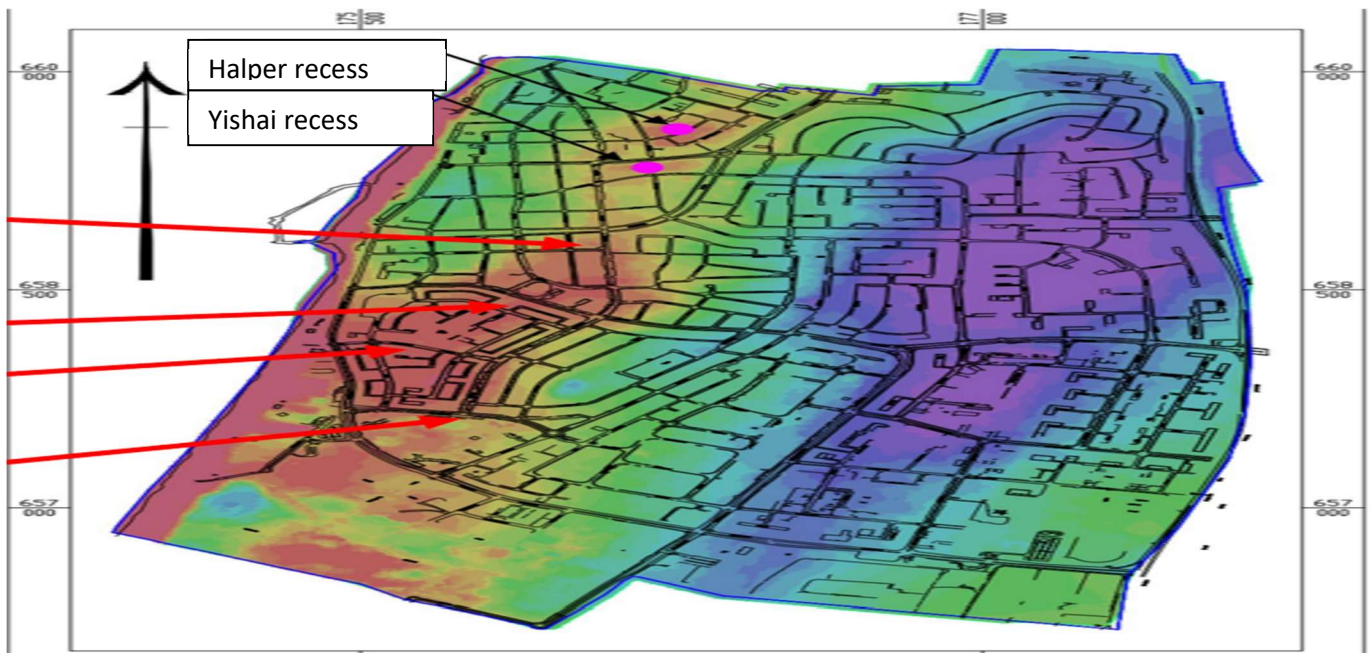


Figure 11. (1)Timeline of quantity of faults, (2)percentage and (3)Pareto of faults per location

Figure 12 “As is” physical system

Topography



Number	Minimum Elevation	Maximum Elevation	Color
1	0.00	6.50	
2	6.50	8.50	
3	8.50	10.00	
4	10.00	11.00	
5	11.00	12.50	
6	12.50	13.50	
7	13.50	14.50	
8	14.50	16.00	
9	16.00	17.50	
10	17.50	19.00	
11	19.00	20.00	
12	20.00	22.00	
13	22.00	24.00	
14	24.00	26.00	
15	26.00	28.50	
16	28.50	31.00	
17	31.00	33.50	
18	33.50	36.50	
19	36.50	40.00	
20	40.00	48.00	

Figure 13. Topography

White noise

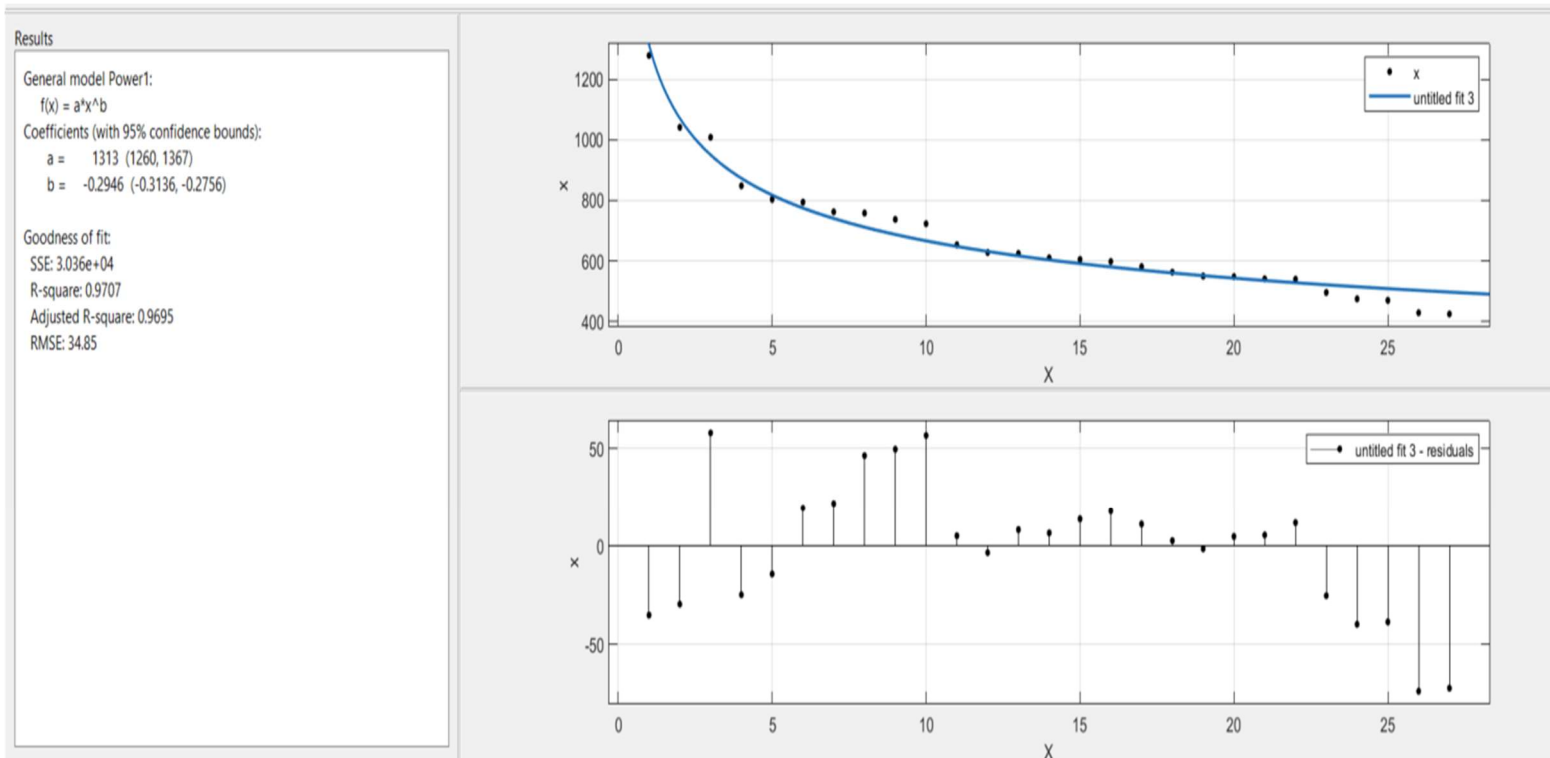


Figure 14. White noise power function and White noise formation, showing repetitive formations that are not related to the magnitude.

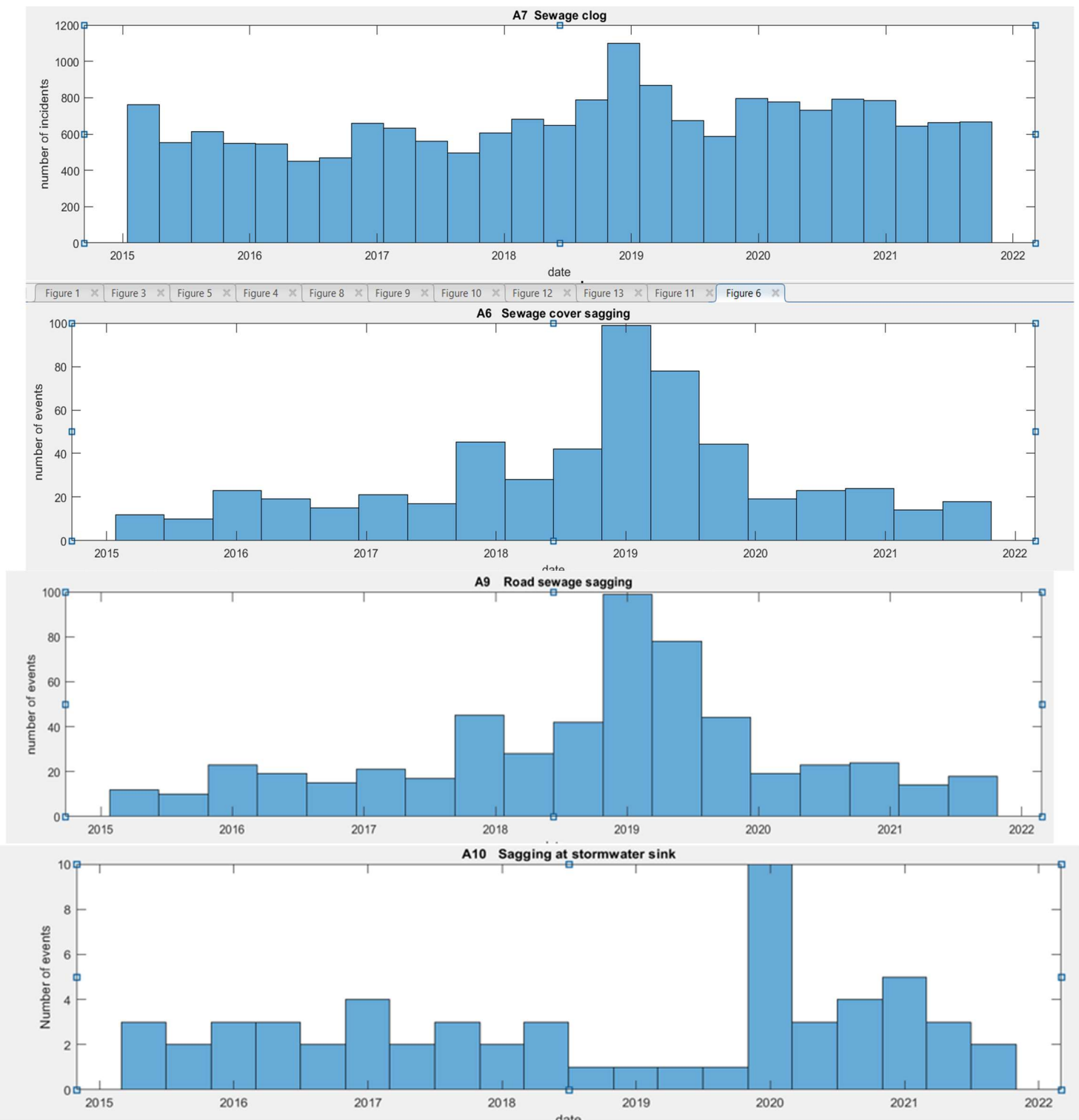


Figure 15. The cause of the “White” noise

Physical forensics

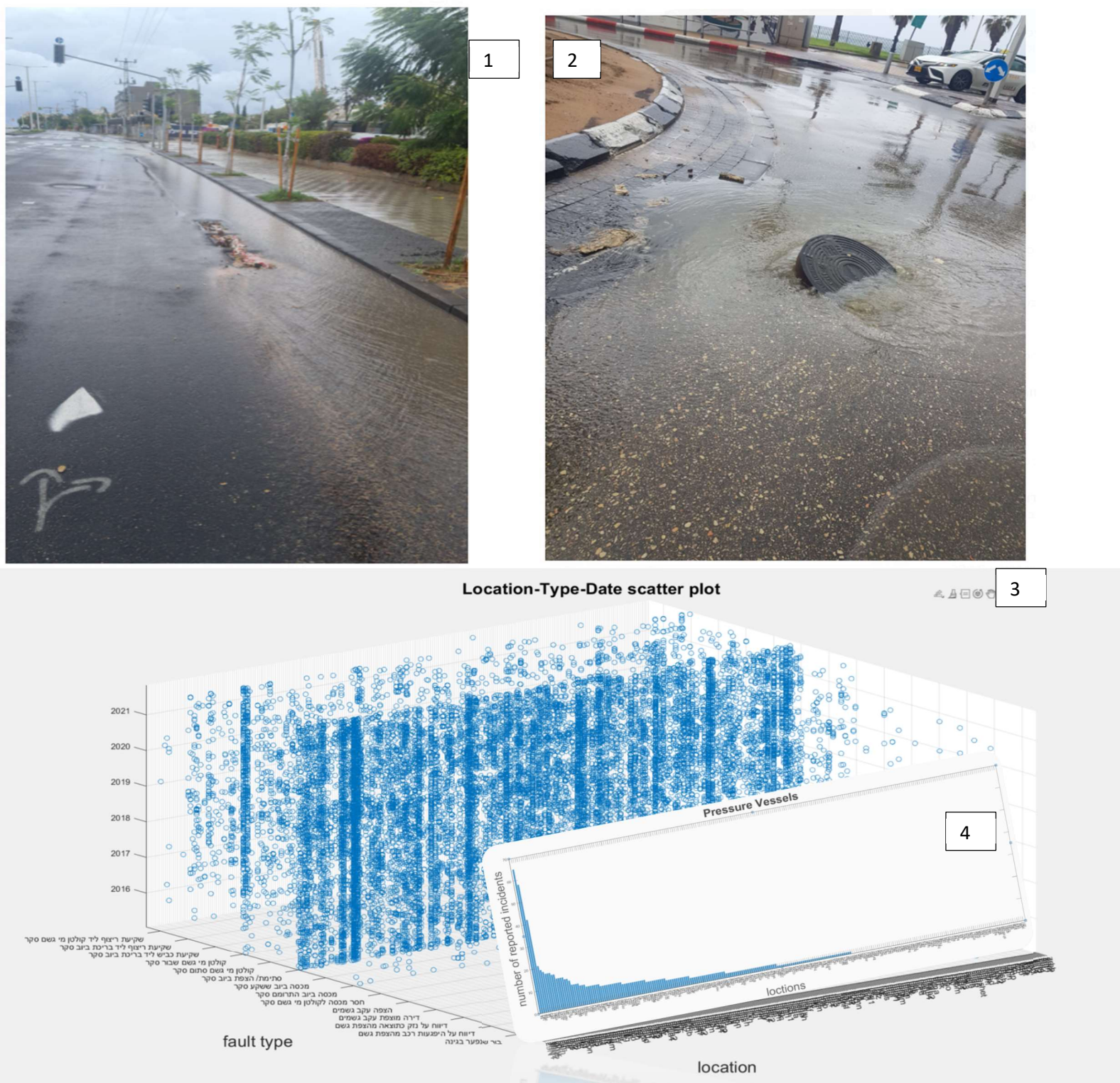


Figure 16. Physical findings. (1) the actual drainage transfer system, (2) a pressure conduit burst a few km uphill (3) 3D scatter plot of faults (4) number of reported incidents of top burst per location.

Figure 17 sewage discharge, water contamination, impairment to sewage systems.
Trapped air effect (Zhou et al., 2004).



Figure 17. Physical findings

Morphology

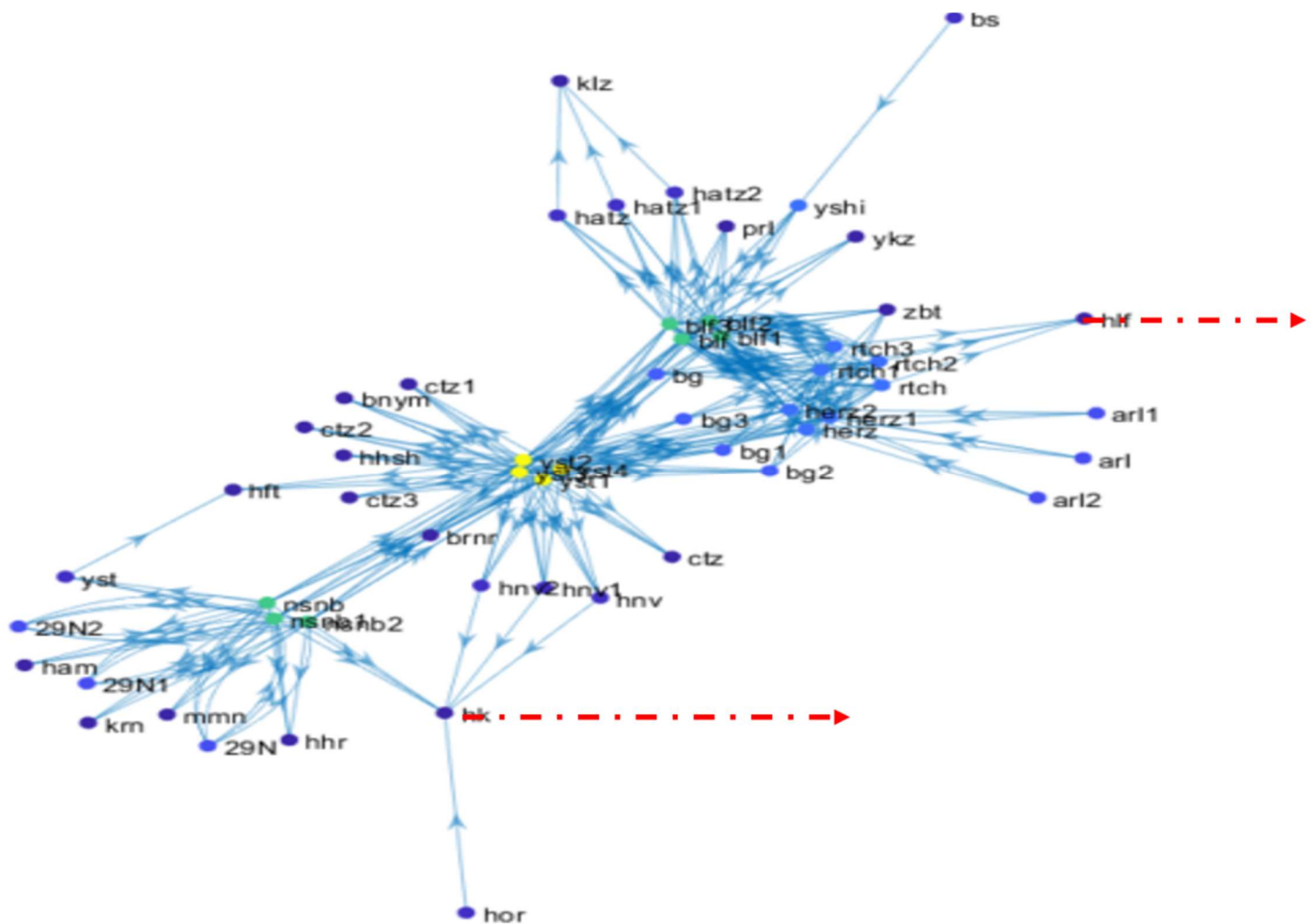


Figure 18 Fault generated network general morphology of the western basin. The hydrological characteristics of the red outlets are given on Figure 12

attractors

Red arrows point to locations of attractors.

Attractors are nodes of the network.

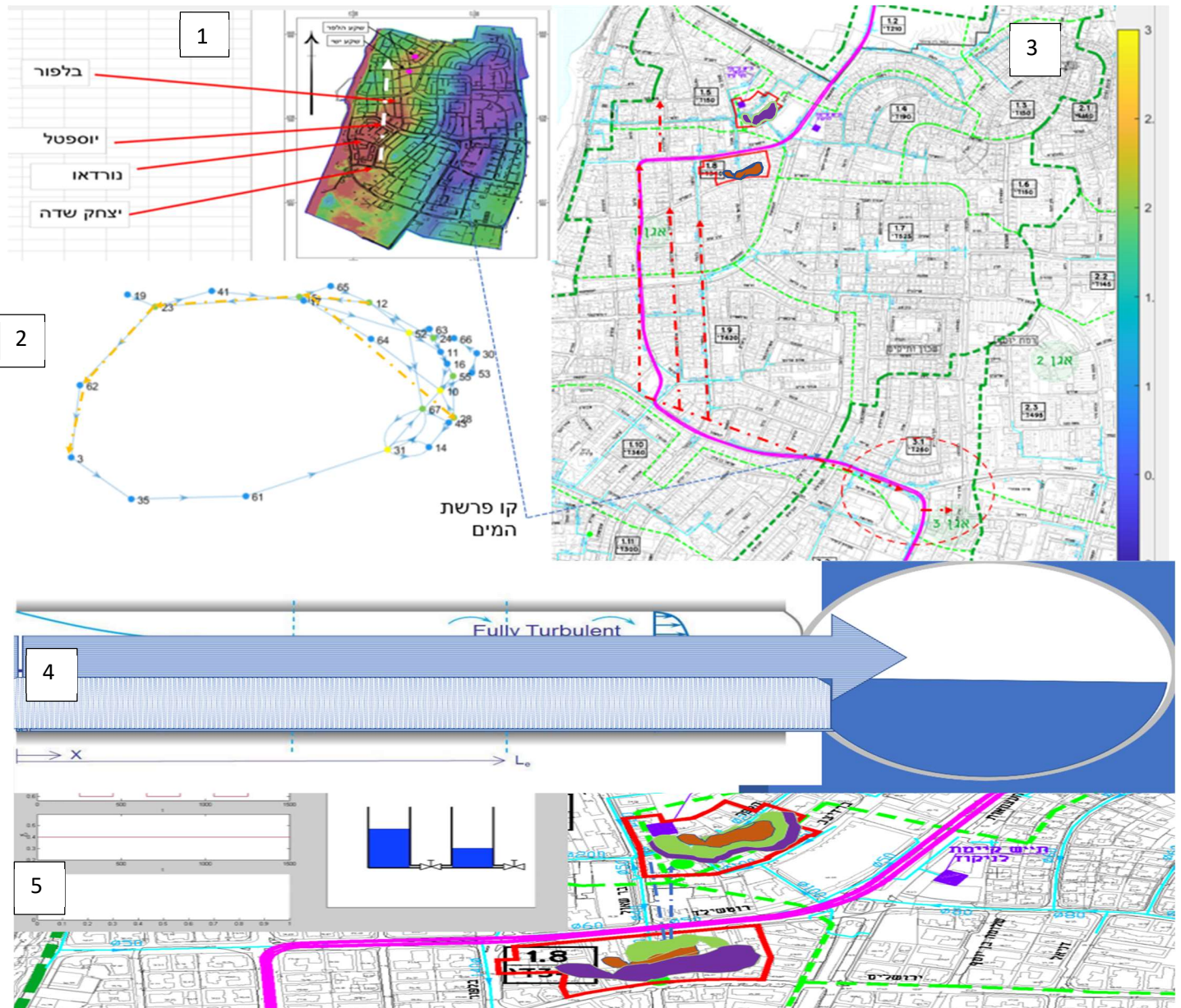


Figure 19. (1) topographical overview (2) a spatio-temporal fault map that is a Zoom-in into (3) a portion of the physical net showing against gradient flows. (4) a suggested explicatory model, and (5) a possible oscillator.

PID Controller

A seasonal pond is suggested.

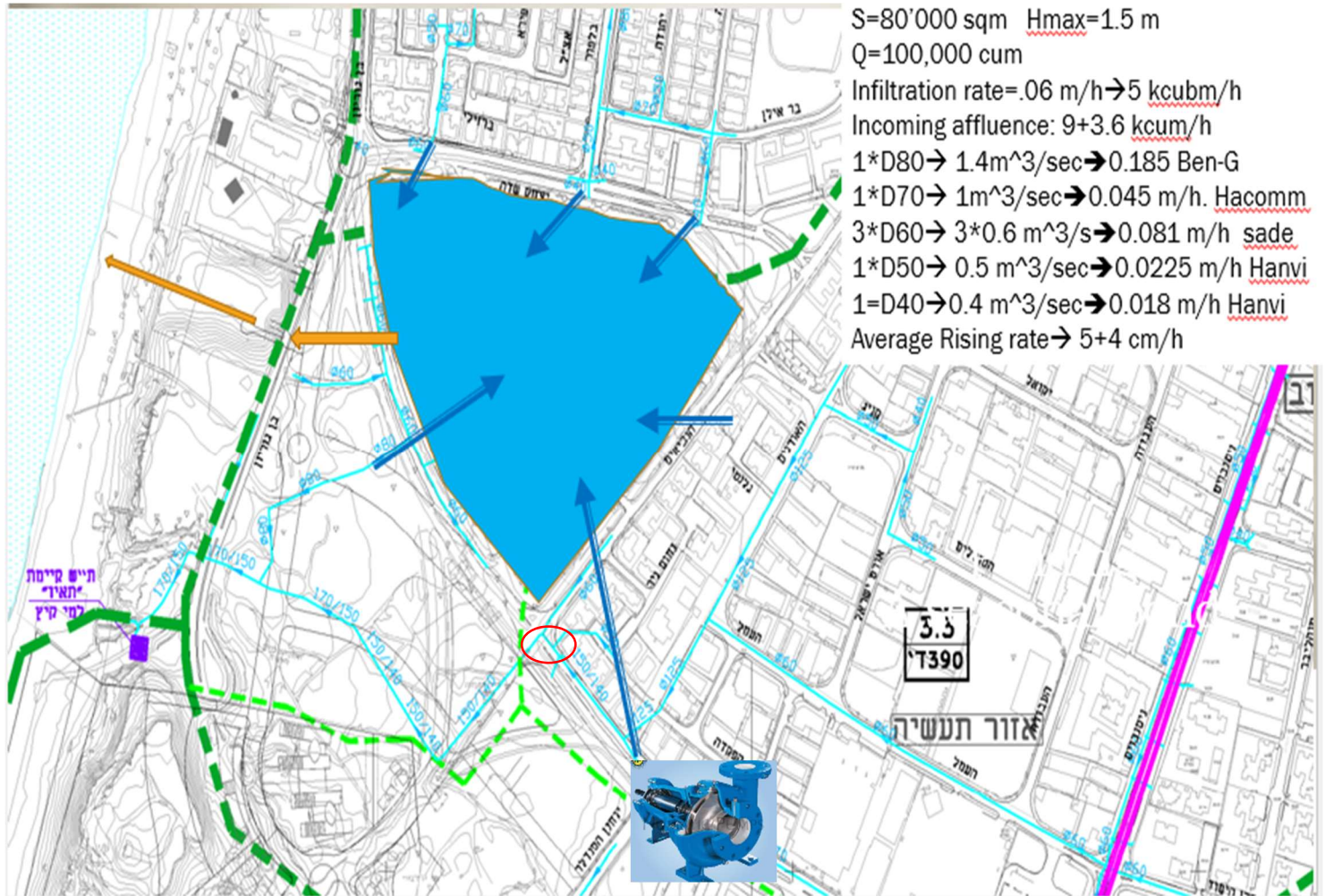


Figure 20. Suggested seasonal pond, ingress and overflow.

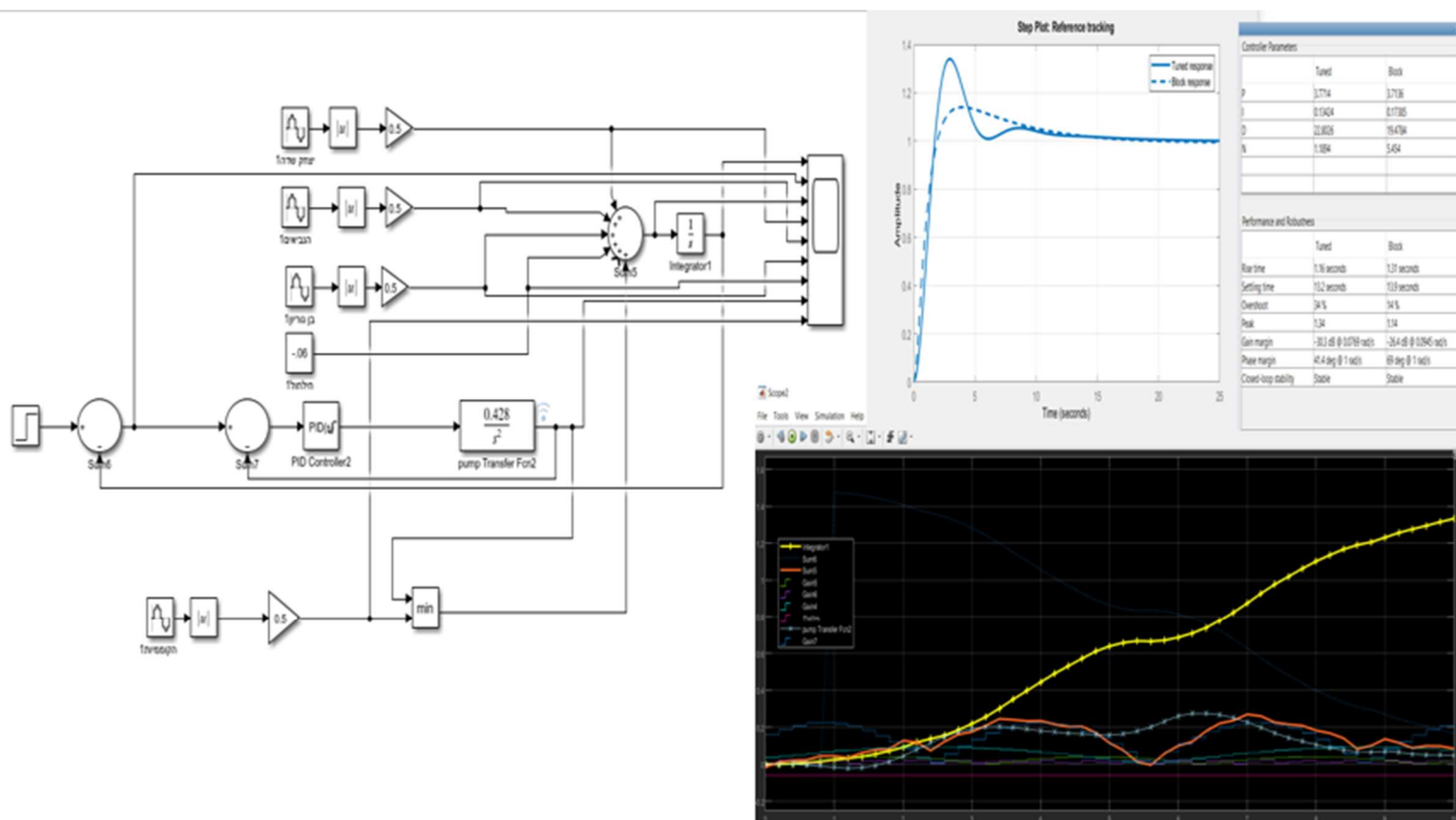


Figure 21. PID system, parameters, and controlled output