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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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MODELLING OF HYDRAULIC FLOW REDISTRIBUTION IN PARALLEL PUMP SYSTEMS

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Abstract. *Relevance.* Efficient operation of parallel pumping systems is challenged by variable water demand and partial-load conditions, which can shift pumps away from their optimal operating range. *Objective.* This study investigates hydraulic flow redistribution in parallel pump systems using internal bypass regulation and develops a numerical framework for analysing its effect on system operating conditions. *Methods.* A steady-state hydraulic model of a parallel pumping system was developed in EPANET 2.2. The model represents two parallel centrifugal pumps, suction and discharge pipelines, a common delivery system, and an adjustable bypass connection between the pump branches. Different bypass conductivity conditions were simulated to evaluate changes in the system characteristic and pump operating points. *Results.* The numerical results show that bypass conductivity substantially affects the hydraulic behaviour of the parallel pumping system. Increasing bypass conductivity changes the system characteristic and modifies the operating points of the pumps, resulting in redistribution of flow within the pumping system. The simulations demonstrate how different bypass conditions modify the hydraulic operating conditions and pump operating points relative to the no-bypass condition. *Conclusions.* The study demonstrates the applicability of EPANET 2.2 for steady-state analysis of bypass-controlled parallel pumping systems at the network level. The proposed modelling

approach provides a basis for evaluating bypass configurations and their influence on hydraulic operating conditions without changing pump rotational speed.

Keywords: hydraulic modelling; parallel pumps; flow redistribution; pumping stations; EPANET; bypass regulation

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ПАРАЛЛЕЛЬ СОРАП ЖҮЙЕЛЕРІНДЕГІ АҒЫНДАРДЫ ГИДРАВЛИКАЛЫҚ ҚАЙТА БӨЛҮДІ МОДЕЛЬДЕУ

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Аннотация. *Өзектілігі.* Параллель жұмыс істейтін сорғы жүйелерін тиімді пайдалану су тұтынудың өзгермелілігімен және сорғылардың ішінара жүктеме жағдайында жұмыс істеуімен күрделенеді, бұл жұмыс режимдерінің оңтайлы жағдайлардан ауытқуына әкелуі мүмкін. *Мақсаты.* Осы зерттеуде ішкі айналма құбырды пайдалану арқылы параллель жұмыс істейтін сорғы жүйелеріндегі ағындарды гидравликалық қайта бөлу қарастырылады және оның жүйенің жұмыс режимдеріне әсерін талдауға арналған сандық тәсіл әзірленеді. *Әдістері.* Стационарлық гидравликалық режимдерді модельдеу үшін EPANET 2.2 бағдарламалық кешенінде параллель сорғы жүйесінің моделі әзірленді. Модельге параллель жұмыс істейтін екі ортадан тепкіш сорғы, сору және айдау құбырлары, жалпы су беру жүйесі және сорғы тармақтары арасындағы реттелетін айналма қосылыс енгізілді. Жүйе сипаттамасы мен сорғылардың жұмыс нүктелерінің өзгерістерін бағалау үшін айналма қосылыстың әртүрлі өткізгіштік жағдайлары бойынша модельдеу жүргізілді. *Нәтижелері.* Сандық модельдеу нәтижелері айналма қосылыстың өткізгіштігінің өзгеруі параллель сорғы жүйесінің гидравликалық режиміне әсер ететінін көрсетті. Айналма өткізгіштіктің артуы жүйе сипаттамасын және сорғылардың жұмыс нүктелерін өзгертіп, сорғы жүйесінің ішінде ағындардың қайта бөлінуіне әкеледі. Модельдеу

нәтижелері айналма қосылыстың әртүрлі жағдайларының жүйенің гидравликалық жұмыс режимдері мен сорғылардың жұмыс нүктелеріне әсерін айналма қосылыссыз режиммен салыстыруға мүмкіндік береді. *Қорытындылар.* Зерттеу EPANET 2.2 бағдарламасын гидравликалық желі деңгейінде реттелетін айналма қосылысы бар параллель сорғы жүйелерін стационарлық талдау үшін қолданудың мүмкіндігін көрсетеді. Ұсынылған сандық тәсіл сорғылардың айналу жиілігін өзгертпей, айналма қосылыстың әртүрлі конфигурацияларын және олардың гидравликалық жұмыс режимдеріне әсерін бағалауға мүмкіндік береді.

Түйін сөздер: гидравликалық модельдеу; параллель сорғылар; ағындарды қайта бөлу; сорғы станциялары; EPANET; перепуск арқылы реттеу

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МОДЕЛИРОВАНИЕ ГИДРАВЛИЧЕСКОГО ПЕРЕРАСПРЕДЕЛЕНИЯ ПОТОКОВ В ПАРАЛЛЕЛЬНЫХ НАСОСНЫХ СИСТЕМАХ

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Аннотация. *Актуальность.* Эффективная эксплуатация параллельных насосных систем осложняется изменениями водопотребления и необходимостью работы насосов в условиях частичной нагрузки. Это может приводить к отклонению рабочих режимов от оптимальных значений, снижению гидравлической эффективности и возникновению неравномерного распределения расходов между насосными агрегатами. В связи с этим актуальной задачей является исследование возможностей регулирования гидравлических режимов путем перераспределения потоков между параллельными насосными ветвями. *Цель.* Исследовать влияние регулируемого внутреннего перепуска на гидравлическое перераспределение потоков в параллельных насосных системах и разработать численный подход к оценке изменения рабочих режимов насосов. *Методы.* Для исследования стационарных гидравлических режимов разработана численная модель параллельной насосной системы с использованием программного комплекса EPANET 2.2. Модель включает два параллельно работающих центробежных насоса, всасывающие и напорные трубопроводы, общую водоподающую сеть и регулируемое перепускное соединение между насосными ветвями.

Проведено численное моделирование различных значений гидравлической проводимости перепускного соединения для оценки их влияния на распределение расходов, гидравлические характеристики системы и положение рабочих точек насосов. *Результаты.* Установлено, что изменение гидравлической проводимости перепускного соединения оказывает влияние на распределение потоков и рабочие режимы параллельно функционирующих насосов. Увеличение проводимости перепуска приводит к изменению гидравлических характеристик системы и смещению рабочих точек насосных агрегатов, сопровождающемуся перераспределением расходов между насосными ветвями. Сравнительный анализ расчетных режимов с перепуском и без него показал возможность регулирования гидравлических параметров системы посредством изменения проводимости перепускного соединения без корректировки частоты вращения насосов. *Выводы.* Результаты исследования подтверждают применимость программного комплекса EPANET 2.2 для численного анализа стационарных гидравлических режимов параллельных насосных систем с регулируемым внутренним перепуском. Предложенный подход позволяет оценивать влияние различных параметров перепускного соединения на распределение расходов и положение рабочих точек насосов. Полученные результаты могут использоваться при анализе и выборе режимов эксплуатации насосных систем с учетом изменяющихся условий водопотребления.

Ключевые слова: гидравлическое моделирование; параллельные насосы; перераспределение потоков; насосные станции; EPANET; регулирование перепуском

Introduction. Fluctuations in water consumption often result in pumping stations operating outside the best efficiency point (BEP), which may lead to increased hydraulic losses and higher specific energy consumption (Walski et al., 2003; Bunn and Reynolds, 2009; Gülich, 2010; Cimorelli et al., 2020). Energy consumption associated with water supply and pumping processes has been widely considered in the context of resource efficiency and sustainable water infrastructure (Plappally and Lienhard, 2012; Coelho and Andrade-Campos, 2014; Bazilian et al., 2011). These issues become particularly relevant in systems with variable hydraulic demand, where pumping equipment must operate under a wide range of flow conditions.

Parallel operation of centrifugal pumps is widely used in water supply and irrigation systems because it provides operational flexibility, redundancy, and the possibility of adapting the supplied discharge to changing demand. From a hydraulic perspective, the operating point of a pumping system is determined by the interaction between the pump characteristic and the system characteristic. Under parallel operation, the total discharge is distributed between the individual pump branches, and changes in hydraulic resistance or operating conditions can

modify both the total discharge and the operating conditions of individual pumps (Karassik et al., 2008; Gülich, 2010). Under partial-load conditions, changes in the hydraulic regime may result in uneven flow distribution, displacement of operating points, and reduced overall performance (Karassik et al., 2008; Wang et al., 2022).

Conventional methods for regulating pumping systems include throttling, pump switching, and variable-frequency drives. Throttling is relatively simple to implement but involves dissipation of excess head through increased hydraulic resistance (Gülich, 2010). Variable-speed control provides a more flexible means of adapting pump operation to changing demand, although its implementation may require modernization of electrical infrastructure and additional investment (Cimorelli et al., 2020; Oshurbekov et al., 2020; Salmasi et al., 2022). In parallel pumping systems hydraulic regulation methods that can modify operating conditions without changing pump rotational speed remain of practical interest.

One such approach is hydraulic flow redistribution through an internal bypass connection. Previous studies have investigated the hydraulic and operating behaviour of parallel pumping systems under different operating conditions (Olszewski, 2016; Olszewski and Arafeh, 2018). In the present study, the bypass is considered as an additional hydraulic connection between the parallel pump branches. The bypass introduces an additional hydraulic branch and changes the effective hydraulic characteristics of the system. Its effect depends on the hydraulic resistance of the bypass and the characteristics of the connected pump and pipeline system. At the same time, bypass flow is associated with additional hydraulic losses and internal recirculation; excessive bypass flow may adversely affect overall system performance. The effectiveness of bypass regulation depends on the specific hydraulic configuration and operating conditions.

Despite the development of hydraulic and optimization approaches to pumping-system analysis, modelling of bypass regulation as an active hydraulic control variable remains comparatively limited. Existing studies have considered bypass arrangements in experimental configurations and related analyses, while systematic numerical investigation of the relationship between bypass conditions, system characteristics, and operating points of parallel pumps remains limited. The review of existing modelling approaches indicates that EPANET and other hydraulic simulators are widely used for analysing pump operation and network hydraulic conditions, whereas bypass regulation has received less attention as an explicit mechanism of flow redistribution (Walski et al., 2003; Rossman, 2020; Olszewski, 2016; Olszewski and Arafeh, 2018; Gan et al., 2025).

EPANET 2.2 provides a network-level framework for analysing hydraulic conditions in pressurised pipe systems and allows pumps, reservoirs, pipes, and control elements to be represented within a common hydraulic model (Rossman, 2020). Previous research has also demonstrated the use of hydraulic modelling and optimization approaches for analysing pumping-

system operation under variable conditions (Cimorelli et al., 2020; Egito et al., 2023; Gong et al., 2025). In the present study, EPANET 2.2 is used specifically for steady-state hydraulic network modelling. The model represents pump behaviour through prescribed head-discharge characteristics and evaluates the interaction between the pump group, pipeline system, and bypass branch. Detailed three-dimensional flow processes inside the pump, including impeller-scale flow phenomena, are outside the scope of the present network model.

The research gap concerns the numerical representation of bypass regulation as an adjustable hydraulic element in a parallel pumping system. The study examines how changes in bypass hydraulic conductivity affect the system characteristic and the resulting operating points under steady-state conditions. The modelling provides a controlled framework for analysing the hydraulic response of the system over a range of bypass conditions and for comparison with experimental or field-scale data.

The aim of this study is to investigate hydraulic flow redistribution in a parallel pump system using steady-state numerical modelling in EPANET 2.2 and to evaluate the influence of different bypass conditions on system head-discharge characteristics and pump operating points. The study focuses on the hydraulic response of the system and does not directly determine electrical energy consumption or pump efficiency. The numerical framework developed in this study provided the hydraulic modelling basis for the subsequent combined experimental and numerical investigation reported by Iovbak and Sennikov (2026) for the corresponding physical configuration.

Materials and Methods. *Modelling concept and system configuration.* The investigated system represents a parallel pumping arrangement consisting of two identical centrifugal pumps connected to common suction and discharge pipelines. The hydraulic configuration includes a source reservoir, two pump branches, a common delivery pipeline, and an adjustable bypass connection between the pump branches. The bypass is represented as an additional hydraulic branch that enables redistribution of flow between the pump circuits. Its hydraulic conductivity was varied to investigate the resulting changes in the operating conditions of the pumping system.

The operating condition of a pumping system is determined by the interaction between the pump head-discharge characteristics and the hydraulic characteristics of the connected pipeline system. For the reference parallel configuration, the total discharge is distributed between the individual pump branches and the operating condition is determined by the interaction between the combined pump characteristic and the system characteristic (Karassik et al., 2008; Gülich, 2010; Todini and Pilati, 1988). When the bypass is opened, the additional hydraulic connection modifies this interaction and changes the operating conditions of the individual pump branches.

In the present study, the bypass is considered as a hydraulic flow-redistribution element rather than a source of additional hydraulic energy. Opening the bypass creates an additional hydraulic connection between the discharge side of Pump 1 and the suction side of Pump 2, thereby changing the hydraulic interaction and flow distribution within the pump group. At the same time, flow through the bypass is associated with hydraulic losses in the bypass pipeline and regulating valve. The effect of bypass regulation is evaluated primarily through changes in flow distribution, system characteristics, and pump operating points.

Numerical modelling in EPANET 2.2. The hydraulic model was developed in EPANET 2.2. The software was used as a network-level hydraulic calculation tool for analysing the steady-state behaviour of the pressurised pumping system. EPANET allows pumps, reservoirs, pipes, junctions, and control elements to be represented within a common hydraulic network and is applicable to steady-state and extended-period analysis of pressurised water systems (Rossman, 2020).

The model consists of two parallel centrifugal pumps, suction and discharge pipelines, a common delivery section, a reservoir, and an adjustable bypass branch. The pump performance of each unit was represented in EPANET by the experimentally determined head–discharge characteristic reported by Iovbak and Sennikov (2026). The characteristic was implemented as discrete flow-head data points, with interpolation performed internally by EPANET. The bypass was introduced as a separate branch with adjustable hydraulic conductivity.

The dimensionless bypass conductivity parameter K_{bp} was used to classify the investigated bypass regulation conditions and as a comparative indicator of the hydraulic capacity of the bypass branch. A value of $K_{bp}=0$ represents the closed-bypass reference condition, while increasing values represent progressively greater bypass capacity. The parameter was not implemented as a native EPANET control variable; instead, the corresponding bypass conditions were represented by changing the setting of the bypass control valve and the hydraulic resistance of the bypass branch.

The present numerical model is limited to the hydraulic behaviour of the connected pipeline network. It does not represent three-dimensional flow processes inside the pump casing or impeller. Impeller-scale velocity fields, detailed turbulence structures, cavitation, and other internal pump-flow phenomena are outside the scope of the EPANET model. The purpose of the simulation is to determine the system-level hydraulic response of the parallel pumping arrangement to changes in bypass conditions.

The hydraulic configuration of the numerical model is shown in Figure 1. The model consists of two parallel centrifugal pumps, suction and discharge pipelines, a common delivery pipeline, and an adjustable bypass branch connecting the pump circuits.

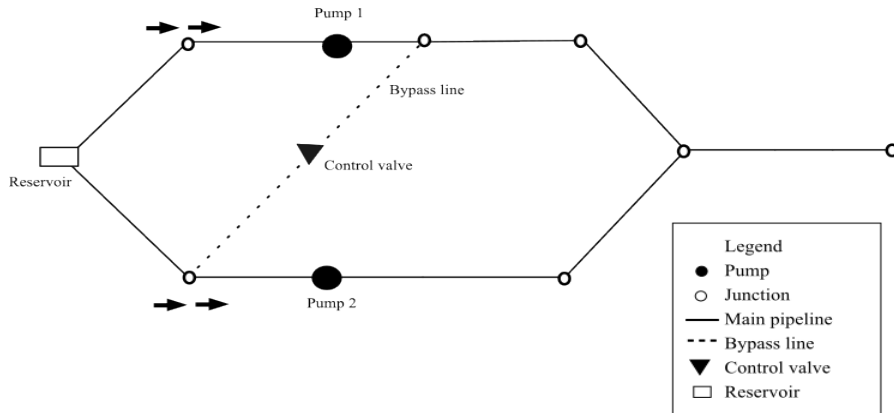


Figure 1. Schematic representation of the parallel pumping system with an adjustable bypass used in the EPANET 2.2 model.

Pump characteristics. Two identical K-20/30 centrifugal pumps were represented in parallel. The nominal discharge of each pump is 20 m³/h, the nominal head is 30 m, the rotational speed is 2900 rpm, and the motor power is 2.2 kW. These parameters correspond to the physical pump configuration used for the experimental investigation and provide a common basis for comparison between the numerical and experimental stages of the research. The corresponding laboratory and EPANET parameters are reported by Iovbak and Sennikov (2026).

The pump performance of each pump was defined using the experimentally determined head-discharge characteristic reported by Iovbak and Sennikov (2026). For implementation in EPANET 2.2, the characteristic was specified as discrete flow–head data points, with interpolation performed internally by the software. The same prescribed pump characteristic was used for both pumps and remained unchanged throughout all bypass scenarios.

For a conventional connected pipeline system, the hydraulic characteristic can be expressed in the general form:

$$H = H_{st} + kQ^2 \quad (1)$$

where H is the required system head, m; H_{st} is the static head, m; Q is the total system discharge, m³/s; and k is the hydraulic resistance coefficient of the system (Todini and Pilati, 1988). Equation (1) is used here to describe the general relationship between system head and discharge and to illustrate the operating-point concept. In the EPANET model, the complete network topology, including the bypass branch, is solved directly rather than being reduced to a single hydraulic resistance coefficient.

For the reference parallel configuration, the operating condition can be described by the interaction between the combined pump characteristic and the system

characteristic. When the bypass is opened, the additional hydraulic connection modifies this interaction and changes the resulting operating conditions of the individual pump branches.

The rotational speed of both pumps was kept constant during the simulations. Changes in the calculated operating conditions were attributed to changes in the hydraulic configuration of the system rather than to variable-speed control.

Hydraulic parameters of the numerical model. The main parameters of the numerical model are presented in Table 1. The geometric parameters correspond to the laboratory configuration used in the experimental investigation. The use of the same principal parameters provides consistency between the numerical model and the physical system.

Table 1. Main parameters of the numerical model.

Parameter	Value
Number of parallel pumps	2
Pump type	K-20/30
Nominal pump discharge	20 m ³ /h
Nominal pump head	30 m
Rotational speed	2900 rpm
Motor power (reference parameter of the physical pump; not used as an input for hydraulic energy-consumption calculations in the present model)	2.2 kW
Suction pipe diameter	50 mm
Discharge pipe diameter	40 mm
Suction pipe length	1.8 m
Discharge pipe length	3.2 m
Bypass pipe diameter	32 mm
Bypass pipe length	3.5 m
Pipe material	PVC SDR21
Hazen-Williams coefficient, C	130
Reservoir water level	0.4 m
Bypass hydraulic conductivity parameter, K_{bp}	0–1.0

The pipeline roughness was represented using a Hazen-Williams coefficient of C=130, corresponding to the PVC SDR21 pipes used in the experimental configuration. The bypass branch had a diameter of 32 mm and a length of 3.5 m.

Bypass regulation scenarios. The bypass hydraulic conductivity parameter K_{bp} was used as the principal comparative variable for analysing the effect of bypass regulation. A value of $K_{bp} = 0$ represents the reference condition with the bypass closed. Increasing values of K_{bp} represent progressively greater hydraulic capacity of the bypass branch.

For each bypass condition, steady-state hydraulic calculations were performed over the investigated operating range. The resulting discharge and head values were obtained for the pumping system and used to determine changes in the system characteristic and pump operating points. The numerical scenarios were

used to examine the hydraulic response of the parallel pump system over a range of bypass conditions while maintaining constant pump rotational speed.

The analysis focused on how changes in bypass conductivity affected the hydraulic behaviour of the system, particularly the system head-discharge relationship, flow distribution between the parallel pump branches, and the resulting pump operating points.

The bypass conductivity was treated as a hydraulic control parameter rather than as a direct energy-saving parameter. No direct electrical power consumption, specific energy consumption, or pump efficiency was calculated from the EPANET simulations. Accordingly, the results of this study are interpreted in terms of hydraulic operating conditions and flow redistribution, rather than as direct measurements of electrical energy savings.

This modelling approach provided a controlled numerical basis for analysing bypass regulation and formed the hydraulic modelling basis for the subsequent combined experimental and numerical investigation of the corresponding physical configuration reported by Iovbak and Sennikov (2026).

Evaluation of the modelling results. The calculated results were evaluated by comparing the operating conditions obtained for different bypass conductivity values with the reference no-bypass condition. The principal comparison variables were total discharge, system head, and the position of the operating points of the parallel pumps.

The calculated head-discharge relationships were used to identify the hydraulic response of the system to changes in bypass conductivity. Particular attention was given to the direction and magnitude of operating-point displacement and to the redistribution of discharge between the parallel pump branches.

The modelling results were not used to assess pump efficiency or electrical energy consumption. Such assessment would require additional pump-performance and power-consumption data. The study focuses on the hydraulic effects of bypass regulation, while the experimental results provide a complementary basis for comparison.

Results. *Effect of bypass conductivity on the system hydraulic characteristic.* Simulations were performed for $K_{bp} = 0, 0.2, 0.4, 0.6, 0.8,$ and 1.0 . Figure 2 presents the calculated steady-state operating points obtained for the different bypass conductivity conditions. Each plotted point corresponds to a separate EPANET steady-state solution, and the total discharge is not prescribed to be identical for different bypass conditions. The points at different K_{bp} values should not be interpreted as a comparison of system head at the same fixed total discharge. The head-discharge relationships presented in Figure 2 represent the system-level hydraulic response of the complete pumping configuration and should not be interpreted as individual pump characteristic curves. The prescribed pump characteristics remain unchanged for all bypass scenarios. The total system discharge is defined as $Q_{total} = Q_1 + Q_2$ where Q_1 and Q_2 are the flow rates

through Pump 1 and Pump 2, respectively. The bypass flow is internal to the pumping system and does not represent an additional external discharge.

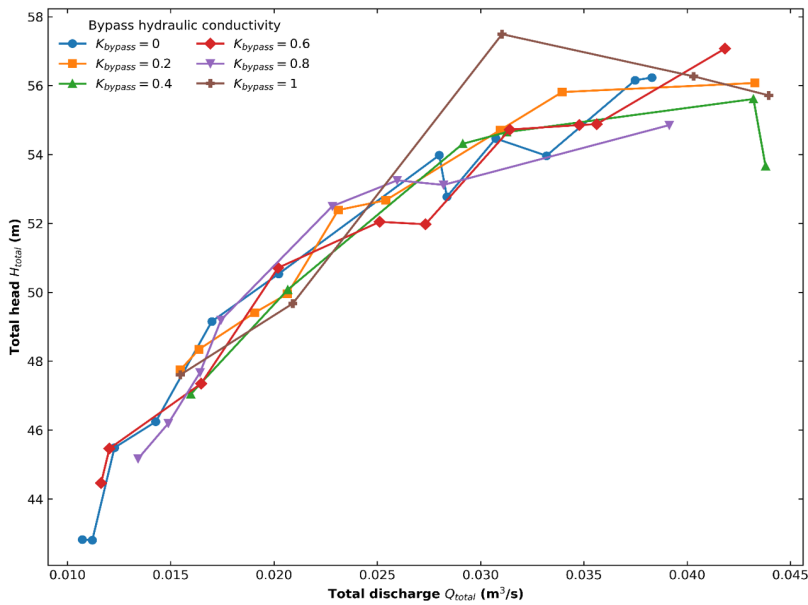


Figure 2. Calculated steady-state operating points of the parallel pumping system for different bypass hydraulic conductivity conditions.

The simulation results demonstrate that variation of K_{bp} changes the hydraulic response of the parallel pumping system. Compared with the reference condition, the introduction of the bypass produces a systematic change in the calculated head-discharge relationship. The modelled system responses differ across the investigated bypass conductivity conditions.

The modelled responses show changes in the system-level hydraulic behaviour as the bypass conductivity is varied. These changes reflect the effect of the additional hydraulic connection between the discharge side of Pump 1 and the suction side of Pump 2 on the interaction between the pump branches and the connected pipeline system. Since the pump characteristics and rotational speed were kept unchanged, the differences between the simulated scenarios are attributed to changes in hydraulic configuration rather than to changes in pump speed or prescribed pump performance.

The results should be interpreted as network-level hydraulic responses of the model. The bypass does not generate additional hydraulic energy. Its opening creates an additional flow path between the pump branches, which changes the distribution of flow within the system. At the same time, flow through the bypass is accompanied by hydraulic losses associated with the bypass pipe and regulating

element. The effect of bypass regulation should be interpreted as a change in hydraulic flow redistribution and system response rather than as an additional source of hydraulic energy.

Flow redistribution between parallel pump branches. The simulation results indicate that changing the bypass conductivity modifies the distribution of flow between the two parallel pump branches. Under the reference condition $K_{bp} = 0$, the bypass does not participate in the hydraulic interaction between the branches. As K_{bp} is varied, the additional hydraulic connection changes the flow conditions within the pump group.

The resulting redistribution affects the operating conditions of the individual pumps while their rotational speed remains unchanged. The numerical results demonstrate that bypass regulation can modify the hydraulic interaction between parallel pumps through changes in the internal flow paths.

The magnitude and direction of the flow redistribution depend on the bypass condition and on the hydraulic characteristics of the connected pump and pipeline system. The results indicate that the bypass hydraulic conductivity parameter can be used as a comparative hydraulic control parameter for investigating different operating regimes of parallel pump systems.

No conclusions regarding pump efficiency or electrical energy consumption are drawn from these results. Such parameters were not calculated in the present EPANET model, as specified in the modelling methodology.

Identification of a hydraulically favourable bypass range. The comparison of the simulated operating conditions indicates that the intermediate bypass conductivity range provides the most favourable hydraulic response among the investigated scenarios. In particular, the conditions corresponding to $K_{bp}=0.2-0.4$ provide a balanced hydraulic regime in which the bypass modifies the flow distribution between the parallel pump branches without the pronounced reduction in system head observed at higher bypass conductivity values. At $K_{bp}=0.6-1.0$, the influence of the internal bypass path becomes more pronounced, resulting in a stronger modification of the system hydraulic response. $K_{bp}=0.2-0.4$ can be considered a hydraulically favourable range for further investigation rather than a universally optimal operating condition.

Comparison of bypass and reference conditions. Comparison of the calculated regimes with the reference condition $K_{bp} = 0$ confirms that the bypass changes the system-level hydraulic response without changing the pump rotational speed or the prescribed pump characteristics.

The principal observed effect is a displacement of the calculated operating conditions resulting from the modified hydraulic configuration. The bypass acts as an internal hydraulic connection that changes the interaction between the parallel pump branches and the common pipeline system.

The numerical results demonstrate the sensitivity of the system to the bypass conductivity parameter. The simulations provide a hydraulic comparison of the

different bypass conditions rather than a direct assessment of pump efficiency or electrical energy consumption.

The numerical results provide a basis for comparison with experimental observations for the same physical configuration.

Discussion. The numerical results demonstrate that bypass regulation can modify the hydraulic response of a parallel pumping system without changing pump rotational speed. The observed changes in the head-discharge relationships and operating conditions are associated with the introduction of an additional hydraulic connection between the pump branches. This is consistent with the general principle that the operating point of a pumping system is determined by the interaction between the pump characteristic and the hydraulic characteristic of the connected system (Karassik et al., 2008; Gülich, 2010). In a parallel pumping arrangement, changes in hydraulic resistance can affect both the total discharge and the distribution of flow between individual pump branches.

The results should be interpreted within the capabilities of the EPANET 2.2 framework. The model describes the steady-state behaviour of the connected pressurised pipe network and represents pump performance through prescribed head-discharge characteristics (Rossman, 2020). EPANET is appropriate for analysing system-level hydraulic interactions between pumps, pipelines, reservoirs, and control elements. The model does not resolve detailed three-dimensional flow processes inside the pump casing or impeller. Impeller-scale velocity fields, detailed turbulence structures, cavitation, and other internal pump-flow phenomena are outside the scope of the present study.

An important aspect of bypass regulation is that the bypass does not constitute an additional source of hydraulic energy. Instead, it provides an additional hydraulic path between the pump circuits and modifies the hydraulic interaction within the system. Flow through the bypass is also associated with hydraulic losses in the bypass branch and regulating elements. Changes in the calculated system characteristics should be interpreted primarily in terms of flow redistribution and changes in operating conditions rather than as direct evidence of increased pump efficiency or energy savings. The hydraulic behaviour of pumping systems is governed by the interaction between pump characteristics and system resistance, and changes in the hydraulic configuration can alter the resulting operating point (Karassik et al., 2008; Gülich, 2010).

The present results do not support considering bypass regulation as a universal replacement for conventional pumping-system control methods. Throttling, pump scheduling, and variable-frequency control are established approaches for adapting pump operation to changing hydraulic demand. Variable-frequency drives modify pump operating conditions by changing rotational speed, whereas bypass regulation modifies the hydraulic interaction between parallel pumps while maintaining constant rotational speed. The relative suitability of these approaches depends on the hydraulic configuration and operational requirements of the pumping system (Cimorelli et al., 2020).

The numerical framework developed in the present study formed the hydraulic modelling basis for the subsequent combined experimental and numerical investigation reported by Iovbak and Sennikov (2026). The corresponding physical configuration used in that study was based on the same principal pump, pipeline, bypass, and model parameters considered in the present numerical analysis. The intermediate range $K_{bp} = 0.2-0.4$ identified as hydraulically favourable in the present simulations was consistent with the corresponding experimental results, where this range was associated with a favourable combination of discharge and head. The subsequent study combined laboratory measurements with EPANET modelling and regression analysis, whereas the present work focuses specifically on the numerical analysis of bypass conductivity and its influence on the system hydraulic response.

A further limitation concerns the assessment of energy performance. The present EPANET model does not directly calculate electrical power consumption, specific energy consumption, or pump efficiency. The numerical results should be interpreted as a hydraulic assessment of bypass regulation rather than as a quantitative evaluation of energy savings or economic performance. Such assessment would require additional pump-efficiency and power-consumption data.

From a practical perspective, the modelling approach can be used as a preliminary tool for evaluating the hydraulic response of a parallel pumping configuration under different bypass conditions. Numerical analysis makes it possible to examine a range of bypass conductivity values while maintaining constant pump characteristics and rotational speed. Selected hydraulic regimes can be compared with experimental results and, where appropriate, subjected to further field verification. Such a staged approach allows the hydraulic behaviour predicted by the model to be compared with experimental results and subsequently assessed under practical operating conditions.

The applicability of bypass regulation nevertheless depends on the specific hydraulic configuration of the pumping station and on the feasibility of installing and controlling an additional bypass connection. The method should be considered a complementary hydraulic control option rather than a universal alternative to existing regulation technologies. Further research should combine numerical modelling with experimental measurements of bypass flow, pump efficiency, and electrical power consumption to evaluate the complete hydraulic and energy performance of bypass-regulated parallel pumping systems.

Conclusion. This study investigated the hydraulic behaviour of a parallel pumping system with an adjustable bypass using steady-state numerical modelling in EPANET 2.2. A network-level hydraulic model was developed to represent two parallel centrifugal pumps, suction and discharge pipelines, a common delivery system, and an adjustable bypass connection between the pump branches. The modelling framework made it possible to systematically examine the response of the pumping system to changes in bypass hydraulic conductivity while maintaining constant pump characteristics and rotational speed.

The simulation results demonstrate that variation of the bypass hydraulic conductivity affects the hydraulic characteristics of the parallel pumping system and changes the resulting operating conditions of the pump branches. The introduction of the bypass creates an additional hydraulic connection between the pump circuits, which modifies the distribution of flow within the system. The bypass hydraulic conductivity parameter can be used as a comparative parameter for investigating flow redistribution and changes in the operating points of parallel pumps without applying variable-speed control.

The results also clarify the hydraulic nature of bypass regulation. The bypass does not generate additional hydraulic energy; instead, it changes the hydraulic interaction between the pump branches and introduces an additional flow path in which hydraulic losses occur. Changes in the calculated head-discharge relationships cannot be interpreted directly as improvements in pump efficiency or reductions in electrical energy consumption. The effectiveness of a particular bypass condition depends on the hydraulic configuration of the pumping system and the resulting redistribution of flow between the parallel pump branches.

The applicability of the proposed approach is determined by the capabilities of the EPANET 2.2 modelling framework. The model is suitable for analysing steady-state hydraulic conditions at the network level, including the interaction of pumps, pipelines, and bypass elements. It does not resolve detailed three-dimensional flow processes inside the pumps, such as impeller-scale velocity fields, turbulence structures, or cavitation. The present study does not directly determine pump efficiency, electrical power consumption, specific energy consumption, or economic performance. The numerical results represent a hydraulic assessment of bypass regulation rather than a direct evaluation of its energy-saving potential.

The modelling framework developed in this study provides a controlled numerical basis for evaluating different bypass conditions and for comparison with experimental results for the corresponding physical configuration. It can be used to identify hydraulic regimes requiring further investigation and to support the selection of operating conditions for further experimental or field assessment.

The study demonstrates that EPANET 2.2 can be applied to the systematic steady-state analysis of bypass-controlled parallel pumping systems and to the investigation of the influence of bypass hydraulic conductivity on flow redistribution and pump operating conditions. The practical relevance of the proposed approach is supported by the developed technical solution for regulating the flow of a pumping station, for which a utility model patent has been obtained (Iovbak et al., 2025). The patented technical solution is consistent with the proposed bypass-based approach and provides a basis for its further investigation and practical development. Further research should combine the present numerical approach with experimental measurements of pump efficiency, bypass flow, hydraulic losses, and electrical power consumption. Such combined numerical and experimental analysis will be required to determine the practical energy performance and economic feasibility of bypass regulation in real pumping stations.

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