www.czasopisma.pan.pl PAN www.journals.pan.pl

JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2021.139011
2021, No. 51 (X–XII): 25–29

Sustainable operation of surface-groundwater conjunctive use systems in the agricultural sector

Tzu-Chia Chen[1], Tsung-Shun Hsieh[2], Rustem A. Shichiyakh[3]

[1] Dhurakij Pundit University, Bangkok, Thailand

[2] Krirk University, Thanon Ram Intra, Khwaeng Anusawari, Khet Bang Khen, Krung Thep Maha Nakhon 10220, Thailand

[3] Kuban State Agrarian University named after I.T. Trubilin, Department of Management, Krasnodar, Russian Federation

RECEIVED 03.04.2021 REVIEWED 01.05.2021 ACCEPTED 28.07.2021

Abstract: Several conjunctive use approaches can be distinguished. Drought cycling of groundwater (GW) usage and storage relies on more surface water (SW) during wetter years and delivers more water from GW during drought years. This method has the benefit of temporal changes in water availability. Additionally, it is usually desirable in areas with internal variability of SW where surface storage of wet-year surpluses is uneconomical, suffer excessive evaporative losses, or cause unacceptable environmental disruption. In previous studies, the purpose of operating the drought cycling was to reduce operating costs. In these studies, the objective function of the proposed model was to minimise the present value cost derived from the system design and operation to satisfy a predefined demand during a finite planning and operation horizon. However, it is important to consider other objectives in operating water resources systems, including minimising water shortages accurately. Hence, in this study, two scenarios were focused on: 1) minimising water shortagages, 2) minimising operational costs. Pareto solutions are then presented with the objectives of minimising costs and water deficit. In this study, the weighting method has been used to extract Pareto options. The results show that reducing costs from 234 to 100 mln USD will increase water shortage from 9.3 to 11.3 mln m^3.

Keywords: agriculture, conjunctive use systems, groundwater, operating cost, surface water, water management

INTRODUCTION

Providing irrigation is necessary to achieve food security for the growing population around the world and maintain livelihoods [Darko *et al.* 2016; Kesuma *et al.* 2018; Molajou *et al.* 2021]. It is especially vital in semi-arid and arid areas where water resources (WRs) are vital for economic development [Foster *et al.* 2018]. However, the agriculture sector in those regions is threatened due competition for low WRs, water shortage, and mismanagement [Bortolini *et al.* 2018]. Therefore, the desirability of creating a flow buffer, both for floods, to protect against drought, and for storage for off-stream water usage, has caused the construction of different sizes of surface ponds [Alimohammadi *et al.* 2009].

Water reservoir systems play a significant role in controlling surface water (SW) and meeting various demands such as irrigation, domestic, industrial, and electricity generation [Salazar *et al.* 2016]. In the last decade, surface storage has been recognised as being challenging due to the following [Alimohammadi *et al.* 2009; Richter, Thomas 2007]:

- significant problems in dam height;
- high cost of tank deposition;
- storage issues with sediment, which reduces storage capacity;
- high evaporation losses, especially in arid areas;
- limited reservoir sites, high population displacement, and other social effects of dam construction;
- a rapid increase in construction and rehabilitation costs;
- environmental constraints.

Groundwater (GW) systems have certain advantages over surface water (SW) systems when considering dam construction [Coe 1990; Dinka 2019; Gude, Maganti 2021; Malek *et al.* 2019; Schilling *et al.* 2019; Zeinali *et al.* 2020]: GW resources usually experience fewer social and cultural problems, less water quality problems, no sedimentation and evaporation, and less cost. Conjunctive operation of SW and GW systems is a vital component for solving the aforementioned problems [LI *et al.* 2018; NAYAK *et al.* 2018; SEO *et al.* 2018]. Thus, the determination of optimal operating rules for the conjunctive management of SW and GW sources is of great importance and quite vital [PHILBRICK, KITANIDIS 1998]. Although early efforts to co-operate GW and SW systems date back to the 1960s [BURT 1964], the conjunctive usage of SW and GW has received increased attention since the late 1990s with the introduction of integrated WRs management [COE 1990].

Conjunctive use of SW and GW is performed in several ways depending on the system components used [AFSHAR *et al.* 2008; 2020b; HAROU, LUND 2008]. A drought cycling system is a conjunctive usage system containing two main subsystems: SW and GW, in an interactive loop that satisfies prespecified demands. In such a system, the confinement subsystems can be considered as competing for interconnected parallel storage facilities, which may reduce many of the problems associated with large-scale surface confinement. Based on the type of GW simulation model, the drought cycling systems are usually modelled as distributed or lumped systems. The lumped method ignores the spatial variability of the properties of the aquifer [AFSHAR *et al.* 2021]. It applies single values for the hydrodynamic parameters of an aquifer. However, the distributed method considers the spatial variability over the entire aquifer [AFSHAR *et al.* 2020]. PERALTA *et al.* [1991] and have highlighted that the distributed GW parameters can be incorporated in a management model with two main techniques: embedding method (EM), unit response matrix (URM).

Assessment of the operation of the drought cycling system during the drought periods is very significant. Water supply is always less than the demand during the drought period. In previous studies which focused on the drought cycling system's operation, the objective function of the model was to minimise the present value of operational costs [AFSHAR *et al.* 2008; ALIMOHAMMADI *et al.* 2009]. However, the coordinated management of SW and GW defines a "conjunctive water use" term in WR management, which intends to improve the deficit [KHOSRAVI *et al.* 2020]. In other words, the purpose of conjunctive water use is to make the most of available water at higher sustainability. For achieving sustainability, all the elements in the system should also be in balance. The sustainable WRs systems can be defined as "those systems designed to contribute fully to the objectives of society while maintaining their hydrological, environmental and ecological integrity" [LOUCKS 1997].

As a novel strategy, two different scenarios were defined to investigate the performance of the drought cycle system in the current study. In the first scenario, the objective function was defined as minimising the operating costs to find the low-cost operating rules. Whereas in the second scenario, the objective function was considered as minimising the water deficit. The scenarios were applied to solve the problem located in New Mexico. Abiquiu reservoir and its downstream watershed of Rio Grande River is the point of attraction in this paper.

MATERIALS AND METHODS

STUDY AREA

The current paper is based on an actual WRs development project and selected based on the available data. The proposed research in the current paper is applied to solve the simplified real-world problem located in the state of New Mexico.

The design of the reservoir and the conjunctive operation of the GW and SW (aquifer and dam) have been investigated, and relevant data taken from the Mexico Consulting Engineers. A 40-season period (2010 to 2020) was chosen based on the historical time series.

DROUGHT CYCLING SYSTEM

Drought cycling of SW and GW refers to integrated SW and GW subsystems with full connections [AFSHAR *et al.* 2020; HAROU, LUND 2008]. As mentioned in the introduction, surface and subsurface subsystems can be potentially interconnected as competing for parallel storage facilities, which may reduce many of the problems associated with large-scale surface seizures. A drought cycling of an SW and GW system is composed of: (1) surface element, (2) subsurface element, (3) demand, (4) water conveyance, and (5) an operating policy subsystem.

In a considered drought cycling system with one surface reservoir (SR) and one aquifer, the river flow is initially stored in the reservoir. Considering the SR, the amount of water is directly transferred to the demand area and/or recharging sites together with the amount of water discharged to the river from the total release from the SR. Water released to the river may be used to satisfy downstream needs, diverted to demand areas or artificial sites. The pumped water from the aquifer may be used to meet part of the demand, or it may be pumped back to the SR if necessary and justified. Total water conveyed to the demand area, which are made from combinations of SR, river diversion to demand area, and aquifer pumping to demand area, will be allocated to satisfy the total demand. A percentage will be lost through evaporation, percolation to the aquifer, and/or returned to the river as irrigation return flow. Precipitation is also considered on the river and demand area. Some percentage of precipitation percolates into the aquifer. There is a hydraulic interaction between the aquifer and river and causes leakage from the river to the aquifer or vice versa.

THE MODEL OF GROUNDWATER (GW)

Conjunctive use systems are usually modelled as lumped or distributed systems [MARTÍNEZ-SANTOS, ANDREU 2010]. The lumped approach treats the entire GW basin as a simple storage reservoir, similar to a surface reservoir (SR). Therefore, stream aquifer interaction and spatial distribution of GW level in the aquifer are not addressed thoroughly. In other words, the modelling is mainly restricted to water accounting and budgeting approaches with no detailed spatial analysis. Distributed models, on the other hand, account for the spatial variability of system parameters, decision variables, and state variables within the aquifer. In a distributed GW management approach, an optimisation model is coupled with a distributed simulation model for aquifer response evaluation to excitations in the domain [KRYSANOVA *et al.* 1999; VANSTEENKISTE *et al.* 2014]. However, since the governing equation of flow in porous media is a partial differential equation (i.e., Bossinesque eq.), it cannot be directly included in any management optimisation model. Therefore, one of the following two methods is usually employed: 1) embedding method (EM), 2) unit response matrix (URM) [PERALTA *et al.* 1991; PSILOVIKOS 2006]. In the EM, the governing GW flow equation's finite difference or finite element approximations are embedded within the optimisation model as part of the constraint set. Therefore, embedding models directly include discretised flow equations among their constraint equations. Whereas, the URM uses a foreign GW simulation model to develop the unit response of the aquifer system to turbulence in pumping and/or recharging at selected points on the slope. In this method, the drawdown at well *k* at the end of the discrete-time period *n* and based on superposition method for *J* number of wells may be given as:

$$Sw(a,r) \ = \sum\nolimits_{t=1}^{r} \sum\nolimits_{s}^{S} B_a(a, \mathrm{s}, r, t) \ Qw(s,t) \qquad (1)$$

where: $Sw(a, r)$ is the drawdown at well and at the end r^{th} of the time period, $B_a(a, s, r - t + 1)$ or unit response coefficient is the change of water table in well *k* at the end of r^{th} the time period with unit stimuli (pumpage or recharge) at the wells at the end of the t^{th} time period, and $Qw(s, t)$ the number of stimuli (pumpage or recharge) at wells, and time period *t* and *S* is the total number of pumping cells.

RESULTS AND DISCUSSION

Climate change for water resources (WRs) and increasing worldwide resource challenges have been important issues for WR management studies. Thus, the determination of optimal operating rules for the conjunctive management of SW and GW sources is of great importance. Previous studies developed a model to optimise the conjunctive operation of the WR system during droughts. A version of the conjunctive operation of the WR system was referred to as a drought cycling system. These studies addressed the design and operation of a GW-SW drought cycling system. In other words, in these studies, the objective function of the proposed model was minimising the present value cost derived from the drought cycling system design and operation to satisfy a predefined demand during a finite planning and operation horizon. However, in order to manage WRs correctly, in addition to the economic efficiency criterion, sustainability criteria are necessary. Overall, conjunctive water use aims to make the most of available water at a lower cost and higher sustainability. At first, in this paper, the optimal design of the system is based on the cost functions provided by previous research. Then, the operation of the system was compared to the following two scenarios:

- minimise water shortage,
- minimise operating costs.

The design parameters, resulting from the design model's solution, are listed in Table 1. As shown in Table 1, to satisfy the total yearly demand of $28.6 \cdot 10^6$ m^3, a reservoir with a net volume of 17.67 10^6 m^3 is needed. Because the cost of direct transfer of water from the tank to the artificial charging area is very high, its capacity is set to zero. As a result, the transfer from the river is possible.

After the drought cycling system was designed with the objective of minimising the total cost of construction and operation, the system is operated by two objective functions: 1) minimise the water shortages, 2) minimise the operational cost. The results of running the model with objective functions 1 and 2 are shown in Table 2.

Table 1. The optimum design capacities and their costs

Component	Construction cost	Operational cost	Capacity$^{1)}$
	mln USD		
Dam	56.600	3.361	17.67
Transfer from dam to demand area	5.391	1.678	2.89
Transfer from dam to the artificial recharge area	0	0	0
Transfer from aquifer to dam	0	0	0
Diversion from the river to demand area	1.906	0.761	1.72
Diversion from the river to the artificial recharge area	2.687	0.639	1.49

$^{1)}$ The unit for reservoir capacity is mln m^3; for others, it is mln m^3 per season.
Source: own study.

Table 2. Operational costs and total deficit for the scenario 1 and 2

Scenario	Deficit costs	Pumping operational cost	Groundwater recharge cost	Conveyance system cost from dam to demand	Diversion system cost from the river to demand	Diversion system cost from the river to artificial recharge areas	Total operational
	mln USD						
1	220.428	8.342	1.955	0.963	1.528	0.782	233.998
2	87.649	7.375	1.679	1.056	1.591	0.671	100.210

Source: own study.

According to Table 2, the operation of the drought cycling system with the objective of minimising total operational costs (second scenario) leads to a significant increase in the water deficit of the system. However, total operational costs in the first scenario have increased 2.5 times in the first scenario. As can be seen in Table 2, other than the cost of water shortages, other costs are not significantly different in the two scenarios. Therefore, it can be concluded that by increasing operating costs, the amount of sustainability index also increases.

Given what has been mentioned, it is clear that studies related to the system's operation from the perspective of minimising operating costs and minimising the water shortage of the system are necessary and essential. In other words, to make the best decision to study the system's operation, the defeated options should be identified and removed from the rest of the options. Figure 1 shows the set of non-defeat solutions of the system with two criteria of minimising operating costs and maximising stability index.

It is carefully seen in Figure 1 that among the available set of solutions, there are 12 non-dominant solutions, none of which are superior to the other. Depending on the existing conditions and priorities for the project, one of these solutions can be selected, and operation policies can be presented based on it.

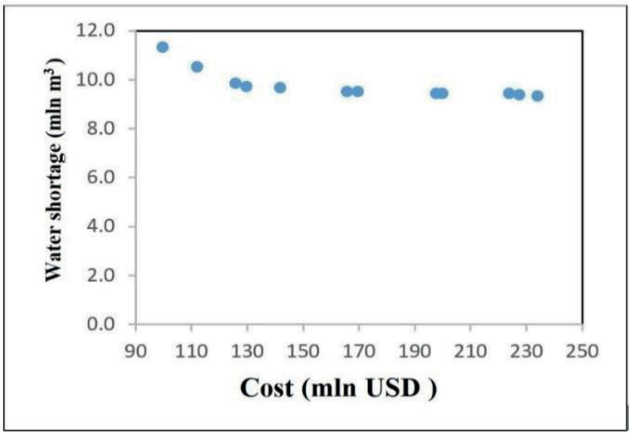

Fig. 1. A set of non-dominant solutions for operating a drought cycling system; source: own study

CONCLUSIONS

Environmental, social, cultural, economic, and technical problems related to surface water compel water resources (WRs) managers to consider groundwater (GW) in management policies to reduce the effect of surface water uncertainty and competing demands. Although opinions on how to plan for integrated WR management remain divergent and continue to evolve, there is a relative consensus on the benefits of integrating GW and surface water (SW) in a conjunctive operation platform as key elements in integrated WR management. Conjunctive use is an alternating use of SW and GW seasonally or yearly to overcome water imbalances and droughts. A version of the conjunctive use system was referred to as the drought cycling system. Advantages of the drought cycle include less development and operational costs, reduced impact of drought, improved flood control ability, less storage capacity, optimal use of aquifer potential capacity, and reduced losses from seepage and evaporation. Previous researchers presented a drought cycling system model to derive the operation policy to evaluate the alternatives for planning integrated use of SW and GW. The objective function of their proposed model was to minimise the present value cost derived from the system design and operation to satisfy a predefined demand during an operation horizon. However, conjunctive water use aims to make the most of available water at a lower cost and higher sustainability. In other words, in order to manage WRs correctly, in addition to the economic efficiency criterion, other criteria are necessary. Hence, in this study, two scenarios were focused on a drought cycling system as follows:
- minimise water shortage,
- minimise operating costs.

This paper showed that total operational costs were very high in the first scenario, and in the second scenario, the water shortage was very high. In other words, in this article, it has been argued that minimising the operation cost would lead to an operating policy with low sustainability. Therefore, the sustainability criterion, such as total water deficit, was emphasised in addition to the economic efficiency criterion. Thus, determining sustainable and low-cost operating rules for the conjunctive management of surface and GW sources is very important. The results of this study are beneficial for evaluating the performance of the WRs system.

REFERENCES

Afshar A., Khosravi M., Molajou A. 2021. Assessing adaptability of cyclic and non-cyclic approach to conjunctive use of groundwater and surface water for sustainable management plans under climate change. Water Resources Management. Vol. 35 p. 3463–3479. DOI 10.1007/s11269-021-02887-3.

Afshar A., Khosravi M., Ostadrahimi L., Afshar A. 2020. Reliability-based multi-objective optimum design of nonlinear conjunctive use problem; cyclic storage system approach. Journal of Hydrology. Vol. 588, 125109. DOI 10.1016/j.jhydrol.2020.125109.

Afshar A., Ostadrahimi L., Ardeshir A., Alimohammadi S. 2008a. Lumped approach to a multi-period–multi-reservoir cyclic storage system optimization. Water Resources Management. Vol. 22(12) p. 1741–1760. DOI 10.1007/s11269-008-9251-y.

Alimohammadi S., Afshar A., Mariño M.A. 2009. Cyclic storage systems optimization: semidistributed parameter approach. Journal – American Water Works Association. Vol. 101(2) p. 90–103. DOI 10.1002/j.1551-8833.2009.tb09842.x.

Bortolini L., Maucieri C., Borin M. 2018. A tool for the evaluation of irrigation water quality in the arid and semi-arid regions. Agronomy. Vol. 8(2), 23. DOI 10.3390/agronomy8020023.

Burt O. 1964. The economics of conjunctive use of ground and surface water. Hilgardia. Vol. 36(2) p. 31–111. DOI 10.3733/hilg.v36n02p031.

Coe J.J. 1990. Conjunctive use – Advantages, constraints, and examples. Journal of Irrigation and Drainage Engineering. Vol. 116(3) p. 427–443. DOI 10.1061/(ASCE)0733-9437(1990)116:3(427).

Darko R.O., Yuan S., Hong L., Liu J., Yan H. 2016. Irrigation, a productive tool for food security – A review. Acta Agriculturae Scandinavica. Section B – Soil & Plant Science. Vol. 66(3) p. 191–206. DOI 10.1080/09064710.2015.1093654.

Dinka M.O. 2019. Groundwater property and composition variability under long-term irrigated area of Wonji Plain, Ethiopia. Journal of Water and Land Development. No. 41(1) p. 37–46. DOI 10.2478/jwld-2019-0025.

Foster S., Pulido-Bosch A., Vallejos Á., Molina L., Llop A., MacDonald A.M. 2018. Impact of irrigated agriculture on groundwater-recharge salinity: A major sustainability concern in semi-arid regions. Hydrogeology Journal. Vol. 26(8) p. 2781–2791. DOI 10.1007/s10040-018-1830-2.

Gude V.G., Maganti A. 2021. Desalination of deep groundwater for freshwater supplies. Chapt. 42. In: Global groundwater. Source, scarcity, sustainability, security, and solutions. Elsevier p. 577–583. DOI 10.1016/B978-0-12-818172-0.00042-6.

Harou J.J., Lund J.R. 2008. Ending groundwater overdraft in hydrologic-economic systems. Hydrogeology Journal. Vol. 16 (6), 1039. DOI 10.1007/s10040-008-0300-7.

Hurd B. H., Coonrod J. 2008. Climate change and its implications for New Mexico's water resources and economic opportunities [online]. NM State University, Agricultural Experiment Station, Cooperative Extension Service, College of Agriculture and Home Economics. [Access 11.02.2021]. Available at: https://aces.nmsu.edu/pubs/research/economics/TR45/welcome.html

Kesuma S.I., Maryunianta Y., Muda I. 2018. Evaluation of irrigation system to support implementation of food security policy. International Journal of Civil Engineering and Technology. Vol. 9(9) p. 600–614.

Khosravi M., Afshar A., Molajou A. 2020. Reliability-based design of conjunctive use water resources systems: Comparison of cyclic and non-cyclic approaches. Journal of Water and Wastewater. Vol. 31(7) p. 90–101. DOI 10.22093/wwj.2020.201234.2924. [In Persian].

Krysanova V., Bronstert A., Müller-Wohlfeil D.I. 1999. Modelling river discharge for large drainage basins: from lumped to distributed approach. Hydrological Sciences Journal. Vol. 44(2) p. 313–331. DOI 10.1080/02626669909492224.

Li P., Qian H., Wu J. 2018. Conjunctive use of groundwater and surface water to reduce soil salinization in the Yinchuan Plain, North-West China. International Journal of Water Resources Development. Vol. 34(3) p. 337–353. DOI 10.1080/07900627.2018.1443059.

Loucks D.P. 1997. Quantifying trends in system sustainability. Hydrological Sciences Journal. Vol. 42(4) p. 513–530. DOI 10.1080/02626669709492051.

Malek A., Kahoul M., Bouguerra H. 2019. Groundwater's physico-chemical and bacteriological assessment: Case study of well water in the region of Sedrata, North-East of Algeria. Journal of Water and Land Development. No. 41(1) p. 91–100. DOI 10.2478/jwld-2019-0032.

Martínez-Santos P., Andreu J.M. 2010. Lumped and distributed approaches to model natural recharge in semiarid karst aquifers. Journal of Hydrology. Vol. 388(3–4) p. 389–398.

Molajou A., Afshar A., Khosravi M., Soleimanian E., Vahabzadeh M., Variani H.A. 2021a. A new paradigm of water, food, and energy nexus. Environmental Science and Pollution Research. DOI 10.1007/s11356-021-13034-1.

Molajou A., Nourani V., Afshar A., Khosravi M., Brysiewicz A. 2021b. Optimal design and feature selection by genetic algorithm for emotional artificial neural network (EANN) in rainfall-runoff modeling. Water Resources Management. Vol. 35 p. 2369–2384. DOI 10.1007/s11269-021-02818-2.

Nayak M.A., Herman J.D., Steinschneider S. 2018. Balancing flood risk and water supply in California: Policy search integrating short-term forecast ensembles with conjunctive use. Water Resources Research. Vol. 54(10) p. 7557–7576. DOI 10.1029/2018WR023177.

Peralta R.C., Azarmnia H., Takahashi S. 1991. Embedding and response matrix techniques for maximizing steady-state ground-water extraction: Computational comparison. Groundwater. Vol. 29(3) p. 357–364. DOI 10.1111/j.1745-6584.1991.tb00526.x.

Philbrick C.R., Kitanidis P.K. 1998. Optimal conjunctive-use operations and plans. Water Resources Research. Vol. 34(5) p. 1307–1316. DOI 10.1029/98WR00258.

Psilovikos A. 2006. Response matrix minimization used in ground-water management with mathematical programming: A case study in a transboundary aquifer in northern Greece. Water Resources Management. Vol. 20(2) p. 277–290.

Richter B.D., Thomas G.A. 2007. Restoring environmental flows by modifying dam operations [online]. Ecology and Society. Vol. 12(1), 12. [Access 10.03.2020]. Available at: http://www.ecologyandsociety.org/vol12/iss1/art12/

Salazar J.Z., Reed P.M., Herman J.D., Giuliani M., Castelletti A. 2016. A diagnostic assessment of evolutionary algorithms for multi-objective surface water reservoir control. Advances in Water Resources. Vol. 92 p. 172–185. DOI 10.1016/j.advwatres.2016.04.006.

Schilling O.S., Cook P.G., Brunner P. 2019. Beyond classical observations in hydrogeology: The advantages of including exchange flux, temperature, tracer concentration, residence time, and soil moisture observations in groundwater model calibration. Reviews of Geophysics. Vol. 57(1) p. 146–182. DOI 10.1029/2018RG000619.

Seo S.B., Mahinthakumar G., Sankarasubramanian A., Kumar M. 2018. Conjunctive management of surface water and groundwater resources under drought conditions using a fully coupled hydrological model. Journal of Water Resources Planning and Management. Vol. 144(9), 04018060. DOI 10.1061/(ASCE)WR.1943-5452.0000978.

Vansteenkiste T., Tavakoli M., van Steenbergen N., de Smedt F., Batelaan O., Pereira F., Willems P. 2014. Intercomparison of five lumped and distributed models for catchment runoff and extreme flow simulation. Journal of Hydrology. Vol. 511 p. 335–349. DOI 10.1016/j.jhydrol.2014.01.050.

Zeinali M., Azari A., Heidari M.M. 2020. Multiobjective optimization for water resource management in low-flow areas based on a coupled surface water–groundwater model. Journal of Water Resources Planning and Management. Vol. 146(5), 04020020. DOI 10.1061/(ASCE)WR.1943-5452.0001189.