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Reservoir Sedimentation and Flushing using Run-of-River Project

Yugandhara Liladhar Devikar, R. A. Oak, S. D. Talegoakar

***Abstract:** Annually sedimentation causes 1 % of storage capacity of the reservoir all over the world. Blockage of intakes in the reservoirs and damage to tunnels/turbines can be also caused due to sediment inflow from the rivers in the catchment area. Due to the problems caused by sediments scouring of sediment from reservoir known as flushing is been done and this technique for removal of sediment is the most effective one. The process of flushing is done by lowering the water level necessarily to erode deposited sediment and also to flush them from/through the intakes and river catchment. The sediment size and other parameters such as the sediment characteristics within the catchment area of reservoir and technique used during the flushing process through the reservoir and also along the geometry of channel can be related to outflow sediment discharge.*

Run-of-the-river projects contribute a major part of power generation in India, but this type of projects face a very common problem of sediment accumulation in the reservoirs due to high amount of sediments coming from mountainous region. These sediments decrease the storage capacity of reservoir and also the life of turbine blades by choking and reacting with it. North and North-East India is facing severe problem of storage depletion in their reservoirs for the power generation. Hence, it is essential to keep proper sediment management plans in reservoirs of these types of projects during planning and design stage. This paper describes the prediction of sedimentation and flushing pattern in the reservoir of usual run of river project in Himalayan region, the paper describes the use of mathematical model simulations. The one dimensional HEC-RAS 5.0.3 was used as numerical modeling for the project and the results of flushing model was also. In this study, monsoon data was used to predict the year wise sedimentation pattern. Eight sets of transport equations (Ackers-White, Meyer Peter Muller, Engelund-Hansen, Laursen, Wilcock-Crowe, Yang, Toffaleti, MPM-Toffaleti.) were used with different sets of time interval to perform the study. The analysis of results and comparison with annual observed sediment volume indicated that simulations using HEC-RAS 5.0.3 with Ackers-White transport equation predicted the sediment load more accurately when the reservoir was operated at FRL. Hence, further studies for reservoir operating at FRL were carried out using the Ackers-White transport equation. Further, the worst condition of sediment accumulation was taken into flushing model to perform flushing analysis. Here, two different combinations of run were performed of 300 cumecs & 400 cumecs discharge for of 3, 6, 9, 12, 15, 18, 24, and 27 hours respectively. By analyzing the results coming from flushing runs, it was concluded that the run performed at FRL for 300 cumec discharge for 24 hours and 400 cumecs discharge for 15 & 18 hours were effective.

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***Correspondence Author(s)**
Yugandhara. Liladhar. Devikar, M.Tech Civil-Hydraulics, Bharti Vidyapeeth (Deemed to be University) College of Engineering, Pune, India.
R. A. Oak, Chief Research Officer (Rtd.), Central Water and Power Research Station P.O. Khadakwasla, Pune, India.
S. D. Talegoakar, Asst Professor, Civil Engineering Department, Bharti Vidyapeeth (Deemed to be University) College of Engineering, Pune, India.

***Keywords:** Reservoir sedimentation, Numerical modeling, HEC-RAS, Run-of-the-river project, Flushing Model, Flushing.*

I. INTRODUCTION

During the last decades dam construction has been increased at a fast rate, predominantly in the tropics and semi-arid areas where high sediment yields are noticeable also reservoir sedimentation. In 1900 there were 42 large dams (i.e. greater than 15 m) while in 1950 and 1986 there were 5268 and about 39000 respectively. An important issue is sustainable use of existing reservoirs, meanwhile building of new reservoirs is relatively difficult due to the new environmental regulations, high cost of construction, and lack of suitable dam sites. On upstream of dam bed aggradations are seen as a result of such disruption. Silt and Sand are commonly found in rivers along-with gravel and large boulders are also been seen which can relate to different forms of sediment particles. Due to the flow of water in the rivers, scour of river bed and its banks eradicates by which the sediment particles from the surface and the sediment thus is carried to the downstream reach till it reaches the dam reservoir. Now if a dam is constructed on this type of river the approach velocity of the flowing water of river is reduced due to obstruction, thereby helping the sediment particles to settle down in the reservoir along the river reach known to be as Reservoir Sedimentation. This reservoir sedimentation results in loss of storage capacity of Reservoir (Bowonder 1985). The sedimentation problem can be solved by planning its stage and by predicting the sedimentation in future also, proper management of dam operations can be planned for evading sedimentation. Reservoir sedimentation studies are essential for keeping a check on siltation over the years after closure of dam and intake gates. To check the detail sediment transport, numerical/mathematical analysis using softwares can be used instead of physical models for sedimentation analysis which is reliable for future predictions. Along the river reach in the head race tunnel i.e. along the upstream of the river run-of-river projects are generally designed with very little storage in the reservoir. The dam is operated for power generation by using the difference in the natural elevation of river reach. Where high sediment concentration is found out these projects are located at such rivers like river flowing in the himalayan regions. The removal of sediments and sediment capacity restoration in the reservoir is typically achieved by hydraulic flushing by using low level outlet which leds to increase in flow velocity. For simulating the sediment profile along the river and reservoir, hydraulic & mathematical and/or numerical models are very useful tools (Morris and Fan 1997) during the design and procedure of the run-of-river projects.

Mainly in Indian dam reservoirs such project are succeeded where sediment management and its removal is being done by hydraulic flushing techniques. Mathematical & physical model studies are successfully done by deciding the design of various components of the project and flushing plan & operation is discussed in this paper. For prediction of reservoir sedimentation study 1D numerical model based on HEC-RAS is used and numerical model analysis for flushing of the reservoir. This study has been carried out to analyze the typical run of river project sedimentation pattern also with the provision for flushing by drawdown flushing technique in Himalayan region by using the low level sluice spillways to scour the deposited sediment in the reservoir.

1.1 Objectives and scope of this paper

- To predict long term sedimentation pattern in typical Himalayan run-of-river projects.
- To recommend most suitable sediment transport equation when simulation is carried out using HEC-RAS model in Himalayan region.
- To identify the worst condition sedimentation profile for flushing analysis.
- To recommend a proper flushing schedule for optimal use of the reservoir.

II. MODEL STUDIES

The dam has been proposed with four openings of low level sluice spillways of size 9.8m width and 12.2m height and is recommended to be functioned between Full Reservoir Level (FRL) elevation RL. 1020 m and Minimum Draw Down Level (MDDL) elevation RL. 1009 m. The reservoir available gross storage is 31.22Mcum and the available live storage is 8.8Mcum. A live storage of 4.5Mcum is required to meet the diurnal daily peaking requirement of three hours. The river bed level at the dam site is of the order of 920m. The average annual sediment inflow for the catchment area of 1338sqkm. As the sediment inflow within the river reach is more than that of the storage capacity of the reservoir, due to which hydraulic flushing of the deposited sediment is used for the required inflow and also restoration the storage capacity of the reservoir. Mathematical/Numerical model studies were used to optimize the flushing operation. To estimate the sedimentation profile and total amount of sediment inflow in the reservoir one-dimensional mathematical model studies is used and then sediment flushing from reservoir is carried out. The entire river reach length is about 4.5 km upstream and 600 m downstream of the dam axis and is replicated in the model. The layout of the river of the study reach is given/shown as below.

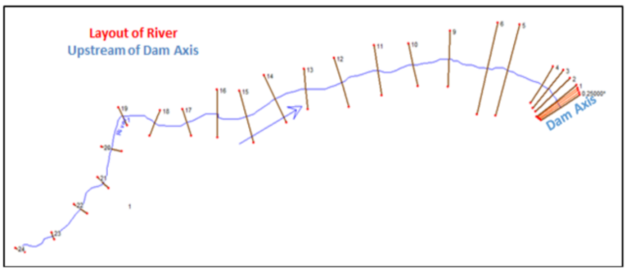

Figure 1. Plan of River Cross-Section

2.1 The one-dimensional model, HEC-RAS 5.0.3

In this study, the 1D model, HEC- RAS 5.0.3 (USACE 1993, 2007) developed by the US Army Corps of Engineers at the Army's Hydrologic Engineering Centre is used to simulate sediment deposition pattern within the dam reservoir. HEC-RAS 5.0.3 is a simulation 1D model which performs the changes in river bed changes and also the sediment pattern within the dam axis, the model is basically a movable open channel flow numerical model, this model also performs the scour and/or deposition over adequate time periods or years. HEC-RAS 5.0.3 procedures steady flows of variable time periods containing discharge hydrographs. By standard step method calculation of water surface profiles are calculated for each flow and is solved by the energy and continuity equations. With the help of user specified loss expansion and contraction losses are calculated whereas Manning's equation calculates the frictional loss. By means of continuity of sediment, variations of sediment along the reach length is calculated with respect to time and distance along-with the study reach for the total sediment load, volume and gradation of sediment that is scoured or deposited cross-section elevations and the armoring of the bed surface. Outflow of sediment at the tail race tunnel of the study reach is also been calculated. Using the sediment grain size fraction the sediment calculations are performed thus allowing the simulation of sediment armoring and hydraulic sorting. The HEC-RAS 5.0.3 model is also very much capable of simulating, channel dredging, networks of streams, and various levee and encroachment alternatives. While maintaining the select rule curve the model can simulate the flow through reservoir. There are various methods by which the sediment deposition pattern can be computed and future predictions for sediment accumulation in the reservoir can be noted down and selection of data sets can be done.

2.2. Sediment deposition using numerical model

In HEC-RAS 5.0.3 the main input data that must be included is the cross-sections area of river reach, bed material grain size distribution and its graph, upstream and downstream boundary data, relation of sediment versus discharge, reservoir operation rule curve, and equations of sediment transport (USACE 2007). The above given data were available for this the HEC-RAS simulation and the project was set up using 1-D numerical HEC-RAS 5.0.3 model and simulation of sediment deposition in the reservoir were performed. Cross sectional survey of the river reach was done which covers reach of 4500m upstream side of dam site and 600m downstream side were available at interval 50m to 200m respectively and therefore model inputs were given to mimic the reservoir and river reach geometry. Discharge data were observed on interval of 10 days at for the period from 1978-79 to 2007-08 and it was studied and three hydrographs mainly for flow of minimum, average, and maximum were recorded on the same interval of 10 day during the period. It was observed that the maximum annual flow volume is observed during the year 1987–1988. For year 1980–1981, 10 daily maximum flow hydrograph and hydrograph is chosen for the model simulation because they are the critical hydrographs for study from sedimentation point. In 1-D model simulation given hydrographs data was converted into stepped hydrographs and is used as upstream boundary. Below fig 2. is the hydrograph for the daily maximum flow.

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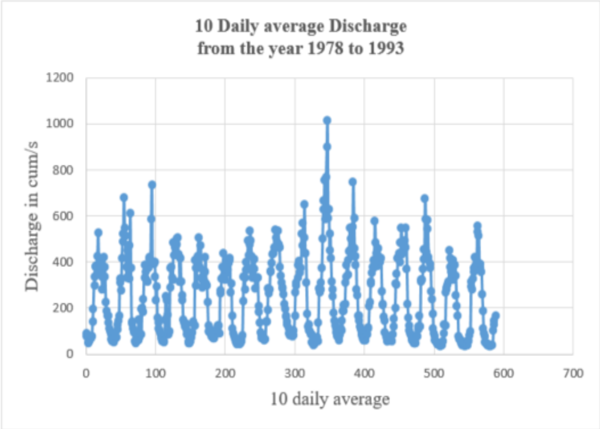

Figure 2. Flow hydrograph used in the 1-D simulation model.

Survey along the river reach was also performed for finding the bed material grain size distribution and average curve was found out. Analysis of daily discharge data along with sediment data were found out also sediment load versus discharge curve (Figure 3) was plotted and used as model input as represented below.

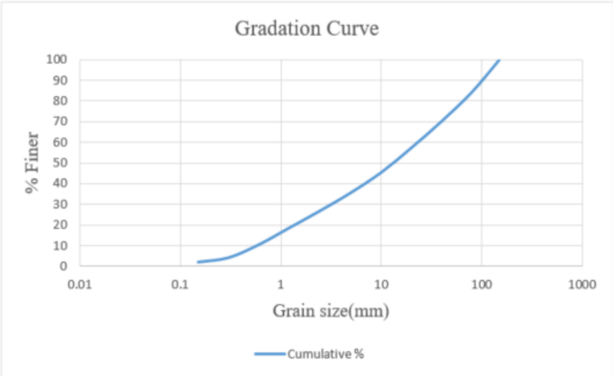

Figure.3 Grain Size Distribution Curve for the study area/model.

III. SIMULATION OF SEDIMENTATION PROFILE

Generally, long-term simulations by one-dimensional mathematical model are performed to estimate the probable sedimentation profile in reservoirs. In the present study, the sedimentation profiles are found by considering the extreme case when the reservoir is filled up to the FRL of El. 1020 m and considering spillway crest level El.970 were selected.

The one-dimensional model, Hydrologic Engineering Centre–River Analysis System (HEC-RAS) version 5.0.3 developed by the U.S. Army Corps of Engineers, was applied for prediction of long-term sediment deposition pattern within the reservoir. Cross sections were available at 50 m interval for the reach of 600 m near dam axis. The model solves the one-dimensional energy/momentum equation to obtain the cross-section averaged hydraulic parameters. The sediment transport potential is then computed at each cross section and the sediment continuity equation is solved for the control volume between consecutive cross sections to compute the sediment deposition level. The river plan and cross sections were used to define the reservoir topography in the model. The discharge hydrograph and measured sediment load were the other input parameters used in the model to predict the long-term sediment deposition pattern.

Volume of reservoir below the crest level of the spillway (El. 970 m) is 21.68 Mm^3, which will be permanently locked upstream of the dam. Hence, based on the above sediment yield, the sedimentation profile may be attained in about 29 years if the reservoir is operated without any flushing during this period. Suspended sediment load measurements carried out by the project authorities at the dam site for a short period indicated that the quantity of suspended sediment at dam site during the years 1978, 1979 and 1980 was 2.168 Mm3, 1.457 Mm3 and 0.454 Mm3, respectively; that is, a total of 4.08 Mm3 for 3 years. Considering the measured suspended sediment load, the above profile will be attained in about 2.5 years.

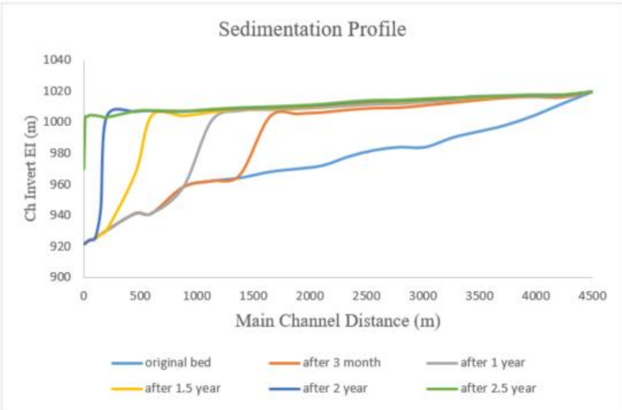

Figure 4. Sedimentation profile for the study area/model.

3.1 Selection of Flushing Discharges

The flushing discharges were selected based on the available flow during monsoon season. Flood hydrograph was there from 1978-78 to 2007-08. It was observed from the hydrograph that the flood of approximately 300m^3/s & 400 m^3/s takes place every year in monsoon season. Hence, flushing discharges have been worked out based on the average annual flood flows for the monsoon months during June to September considering at least one flushing during each year. To optimize the flushing operation, experiments were carried out for flushing discharges of 300 & 400 m^3/s for 3, 6, 9, 12, 15, 18, 24 and 27 hour duration.

IV. EXPERIMENTAL STUDIES AND RESULTS

Experiments for flushing were initially conducted for discharge of 300 m^3/s. The water level in reservoir was maintained at FRL of El. 1020 m at the beginning of the flushing simulation. After stabilization of flow, all spillway gates were opened fully to lower the water level and establish riverine flow conditions. The flushing with the constant discharge was simulated in the model for 3 h. After the flushing, the bed levels along each cross section in the entire reach of the reservoir were measured. The quantity of material flushed in 3-h duration through the spillway was also measured volumetrically. The experiments were repeated to simulate cumulative flushing duration of 3, 6, 9, 12, 15, 18, 24, and 27 h.

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The bed levels on each cross section and volume of flushed sediment collected in the trap downstream of the dam were measured volumetrically after every flushing.

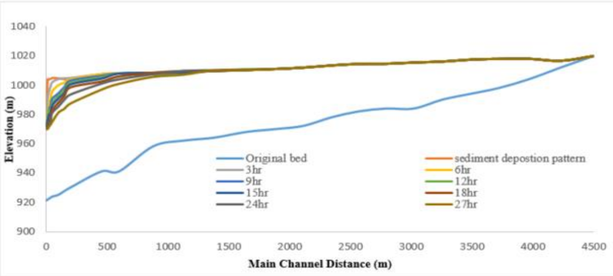

Figure 5. Longitudinal section after flushing (Q = 300 m3/s).

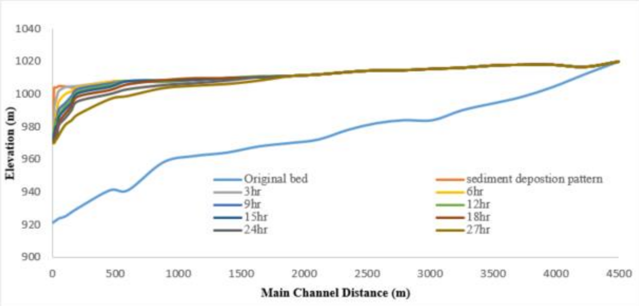

Figure 6. Longitudinal section after flushing (Q = 400 m3/s).

Figure 5 & 6 shows the longitudinal section of bed profiles for various durations. Table 1 gives the quantities of sediment flushed out during various periods of flushing.

Flushing duration (h)	Sediment flushed (Mm3)	
	Flushing discharge 300 (m3/s)	Flushing discharge 400 (m3/s)
3	1.8659	2.65269
6	2.156	2.986
9	2.7176	3.5698
12	3.1893	4.5566
15	4.2326	5.7932
18	5.2632	6.5203
24	6.2892	7.5566
27	7.3503	8.9166

Table 1. Quantity of Sediment flushed in various discharge

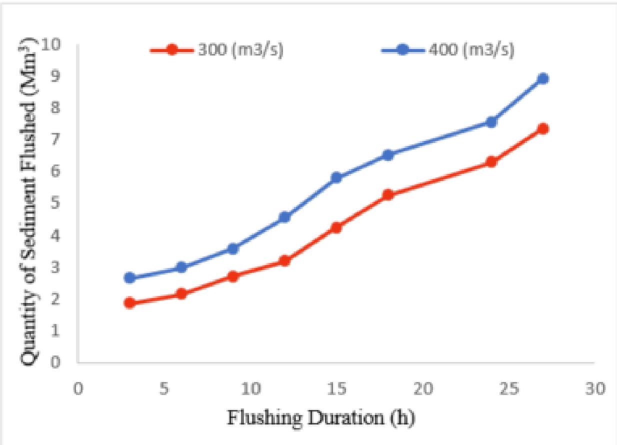

Figure 7. Quantity of sediment flushed.

V. DISCUSSION

The total volume of siltation in the 4.5 km reach of reservoir according to the sedimentation profile with deposition up to El. 970 m is 21.68 Mm^3. To attain this sedimentation level, it would take about 2.5 years of operation without any flushing of reservoir as the incoming yearly sediment load is 8.672 Mm^3/year only. It was observed from the experiments of flushing with discharge of 300 m^3/s and 400 m^3/s that flushing is very effective in the initial 15-h duration. The bed levels plotted in figures 5 and 6 indicate that the effect of flushing extends to a distance of about 1000 m from the dam axis. The experiments also indicated that for all flushing conditions, effect of flushing is prominent up to a distance of about 1.8 km upstream from the dam axis when the flushing is carried out for longer durations. The quantity of sediment removed from the reservoir and the storage capacity thus restored in various durations of flushing are presented in figures 7 for different flushing discharges. It was observed that 6.2892 Mm^3 of sediment was flushed out with the discharge of 300 m^3/s in 24 h duration and 5.7932 Mm^3 & 6.5203 Mm^3 with discharge of 400 m^3/s in 15-h & 18-h duration. The water level above the spillway crest is 50m for the sedimentation profile with deposition up to El. 970 m and the volume of siltation in the 4.5km reach of reservoir is 21.68 Mm^3.

The experiments indicated that the quantity of sediment removed from reservoir and the storage capacity thus restored in 18-h is 6.5203 Mm3 with flushing discharge of 400 m^3/s. The quantity of sediment removed from reservoir by flushing and the storage capacity thus restored for all the experiments presented in tables 1 indicated that maximum scour occurred in the first 12 h. Subsequently, the rate of sediment transport reduces and an equilibrium profile (stable slope) will be attained if the flushing is continued. Considering the annual incoming sediment load of River and performance of flushing of reservoir achieved in the model, it can be seen that one flushing during the monsoon month with a discharge of 300 m^3/s or above is suitable to sustain the reservoir capacity. A reach of about 4.5 km of River covering the reach of 0.6 km downstream of dam axis was replicated in the present studies. The sediment size used in the model was used as the same used gathered from HEC-RAS sediment simulation data to match the incipient motion criteria for sediment movement during flushing. The sediment size was selected based on the median size of sediment particles on the river bed. When the project becomes operational and impoundment starts, finer particles from suspended load also will settle in the reservoir. The gradation (size composition) of reservoir deposition will be different from the original river bed material and most probably the percentage of finer material will be more. Hence, the amount of sediment removed by flushing will be more than model simulations.

VI. CONCLUSIONS

Sediment management to sustain the functional life of reservoirs is the most important aspect in various stages of planning and operation of the run-of-river hydropower projects.

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Hydraulic model studies can be used as an important tool during the decision making at all the stages of the projects. Simulations carried out on a hydraulic model for the drawdown flushing of the reservoir is presented in this paper. Simulations of drawdown flushing were conducted on HEC-RAS model for various durations and discharges for sedimentation profiles.

Following are the major conclusions from the present studies:

- For the sedimentation profile with deposition up to El. 970 m with flushing discharges of 300 m^3/s and 400 m^3/s, it is possible to flush out 6.2892 Mm^3 and 6.5203 $Mm^3$of sediment in a flushing duration of 24 h & 18 h respectively.
- Studies indicated that prominent flushing discharge would be 400 m^3/s and flushing is not effective beyond an upstream distance of 1700 m from the dam.
- One flushing during the flood season when the discharge is 400 m^3/s or higher would be suitable to remove the annual incoming sediment load.

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AUTHORS PROFILE

Yugandhara Liladhar Devikar, pursuing M.Tech (Civil – Hydraulics) Civil Engineering Department, Bharti Vidyapeeth (Deemed to be University) College of Engineering, Pune, India, completed B.E. from Nagpur Univeristy 2014 Batch.

R. A. Oak, Chief Research Officer (Rtd.), Central Water and Power Research Station P.O. Khadakwasla, Pune, India, B.E. Civil from University of Pune, year 1968. M Tech (Hydraulics) - I.H.E. (Delft) The Netherlands, year 1985, Research Work in CWPRS since the year 1972 to 2005 in hydraulics: Evolving hydraulic design parameters for bridges, barrages, weirs, intakes, and anti-erosion Works with the help of Physical models, Mathematical models, Analytical methods, and morphological studies using satellite data. Retired in the year 2005. After retirement, consultations work to various organizations in the field of expertise. 4 papers published in Assam Water Conferences – Year 2012 to 2015. Revision and updating of "Manual on River Training works", published by Indian Railway Institute (IRICEN), Pune - year 2008. Manual / Guidelines on Design of River Training Works for Water Resources Department, Govt Of Assam – Year 2015. Consultation Works as Hydraulic Engineering Consultant for Organizations in India: WAPCOS, SnC Lavalin, ILFS, IIT Powai, Energy Infratech, DHI, EPTISA, RITES, etc. Teaching to M Tech students in Bharti Vidyapeeth since 2008, on the subjects: Water Resources Engineering, Sediment Transport and River Engineering, Scale modelling, Dams & Hydraulic Structures.

S D Talegoakar, Asst Professor, Bharti Vidyapeeth (Deemed to be University) College of Engineering, Pune, India, M.E Hydraulics (Civil Engineering), Publication: Studies of Spacing of Permeable Spurs in Series ISCIET