Pradeep P. Mujumdar

The UN report released on World Water Day of 2014 predicts a drastic decline in water resources in the next 50 years. India is particularly prone to this problem as it harbours 18% of the world population, but shares only 4% of the world's water resources[1]. While rapid population growth, contaminated rivers, water wastage, chaotic land-use patterns and poor water management are the major challenges faced by our country, climate change is likely to aggravate water-related stresses. Clearly, there is an urgent need to understand the possible impacts of climate change on the declining water resources of the country. Pradeep P. Mujumdar, at the Department of Civil Engineering, Indian Institute of Science (IISc), Bengaluru is precisely attempting to assess such impacts of climate change on the flow pattern of rivers, flooding in the urban regions, water quality, etc. by building theoretical models of hydrology. His work is extremely important in order to arrive at the most suitable policies for India. In recognition of the 'insightful contributions to the study of water resources systems and water resources management in India and in the rest of south Asia'[2], the European Geosciences Union (EGU) conferred upon him the prestigious Alexander Von Humboldt medal in April 2014. The EGU aptly called him the 'founding father of modern Indian hydrological science and practice'[2].

Current Science contacted Mujumdar for his views on a range of water-related issues in the country.

Why did you choose to study water resources?

To be honest, it was more of an accident! After completing my B Tech in Civil Engineering, I was keen on pursuing an academic career and thus got into IIT Kharagpur for an M Tech in water resources. Faculty there was extremely motivating and I was fascinated by the subject. This propelled me to pursue a Ph D in the same area and I eventually landed in IISc. In retrospect, I think it was the right choice for me because besides contributing conceptually to the field, I could also offer field-level solutions that have significantly impacted the lives of people... my professional life has been very satisfying.

What are the main challenges faced by the developing countries with regard to water management?

Developed countries have good infrastructure planned and implemented over a period of time and their population growth is not as rapid as many developing countries, particularly not as high as India's. Consequently, developed countries have efficiently managed their water resources with much ease. Further, effective use of modern technology has also contributed to their efforts in managing water resources. In countries such as India, perhaps the most important need is to plan and improve our infrastructure and put in place appropriate operational and management strategies, keeping in view the projected growth rate of the population. Any such planning effort must consider the factors affecting hydrology at all scales, ranging from a small city to a large river basin.

What are global circulation models and can they be employed to model Indian water systems?

Global climate models or general circulation models (GCMs) are the most credible computer models available today to simulate the response of the climate system to external forcings, such as increase in greenhouse gases. They operate at a global scale and are effective when applied to grids as large as about 250 km × 250 km (Figure 1). But if we are looking at hydrology of a river basin for instance, we need grid sizes as small as about 10 km × 10 km and so it is essential to appropriately adopt the GCMs. An important question hydrologists address is 'what happens to rain?'. Also, what part of it evaporates, what part of it infiltrates and what part flows as run-off? These are the processes GCMs are unable to simulate because the scales at which we look at these processes are much smaller. Also temperature, pressure, etc. are smooth fields which are easy to simulate, but rainfall is non-smooth and hence difficult, especially in the monsoon regions. To put it simply, there are two major mismatches: one is with regard to the spatial scales and the other is with respect to the variables; both pose a challenge. In addition, modelling the impact of climate change on water systems is even more challenging and that is what we are trying to do.

We essentially downscale the GCM simulations in two ways. First, we spatially downscale and second, we relate the well-simulated smooth variables of GCM to non-smooth variables such as precipitation (rainfall), using statistical techniques. Thus the two drawbacks are taken care of, to some extent. However, there is a large uncertainty associated with both the GCM simulations and the hydrologic predictions that we obtain with the GCMs, and quantifying and reducing such uncertainties is the prime focus of our group's research.

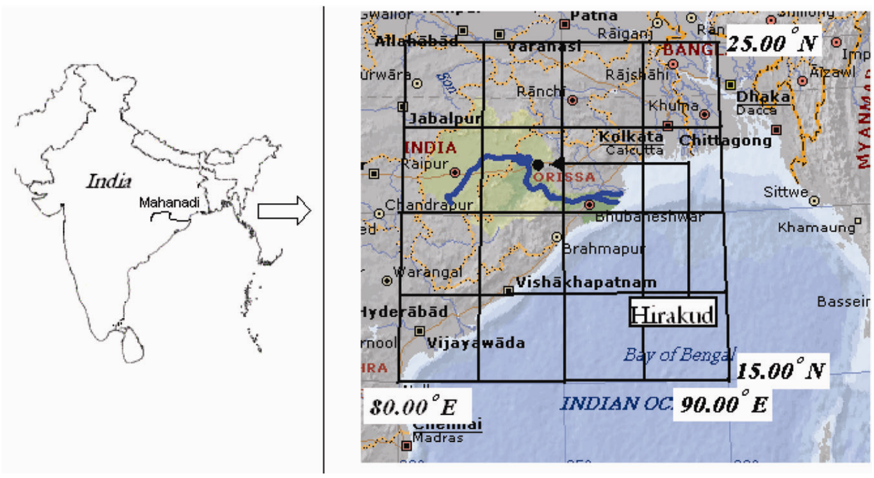

Figure 1. GCM grids overlaid on the Mahanadi. Clearly, there is a need for smaller grids to model the water resources in the Mahanadi[3].

As I mentioned, in India infrastructure development is rather haphazard and ill-planned, without due considerations to hydrologic aspects, especially in urban areas. Therefore, our systems become rather chaotic and do not function smoothly as in the developed countries. So, it is essential to modify the global models and build our own methodology and indigenous technology. Ours is still primarily an agrarian country with small-scale farmers and how we manage water at plot levels in this spatially heterogeneous agricultural landscape becomes extremely important. For instance, a farmer might be growing cotton in a few hectares and his neighbour might be growing wheat. Managing water resources at this level is obviously complex because of the demography and socio-economic status associated with it. So, we cannot blindly apply the already existing models of the West.

An example from your work where not quantifying an uncertainty leads to a wrong prediction

What we predict is the effect of climate change over the next few decades on the water resources. Take Mahanadi river basin for example. There are a number of climate models that may be used to project the streamflow of this river in future, but the model we choose and the scenario we couple it with dictates our results. Scenarios are similar to assumptions on how the future is likely to unfold; for instance, a particular trajectory of CO_2 emissions in future may lead to a specific path of climate evolution, globally. We could thus have a particular model and a scenario combination that projects the increase in streamflow of the Mahanadi, whereas the same model combined with another scenario might project a decrease in streamflow, thus introducing uncertainties in the projections. We quantify such uncertainties and provide projections in a way useful for decision-making.

Any specific work from your lab that you are proud of?

About six years ago, a doctoral student of mine developed a good downscaling model. But I knew we could do more than just that. Hence I posed her a challenge and insisted on developing a model to reduce uncertainties. Acknowledging the uncertainty and quantifying it are in themselves painstaking processes, but I was pressing her to ascertain a method to 'reduce' these uncertainties. We spent a great deal of time thinking about it and eventually developed a method and applied it to the Mahanadi basin successfully. I am happy about this work as it was for the first time that anything of that kind was attempted. More recently, another significant work by my Ph D student addressed non-stationarity in hydrologic extremes of floods and droughts, introduced by climate change. I would consider this as the most important work coming from my group.

Why did you choose the Mahanadi?

Mainly because of data availability. Hirakud reservoir (Figure 2) authorities have been helpful and have been providing us with good data. Over a period of time we have built the database and I am thankful to the Odisha Government and India Meteorological Department (IMD) for the same. But another important reason is that, Odisha is a coastal region known to be sensitive to climate change. Rise in temperature in the state over the last 100 years is 1.1°C, while all over India the increase is only 0.4°C. It is also prone to both droughts and floods, so ironically it is a fertile land for hydrologists to test their theories. Obviously, the Mahanadi drew our attention.

What do your models project for the Mahanadi streamflow?

Mahanadi being a peninsular river the, is monsoon-fed and projections suggest that precipitation in the basin is likely to decrease with time. Therefore, with a high degree of confidence we can say that the average seasonal streamflow is likely to reduce in the Mahanadi. I am using the words 'high degree of confidence' and 'likely' to emphasize that uncertainties still exist. This does not mean that floods will reduce. It might sound counter-intuitive, but floods are caused

Figure 2. Hirakud dam, Odisha[4].

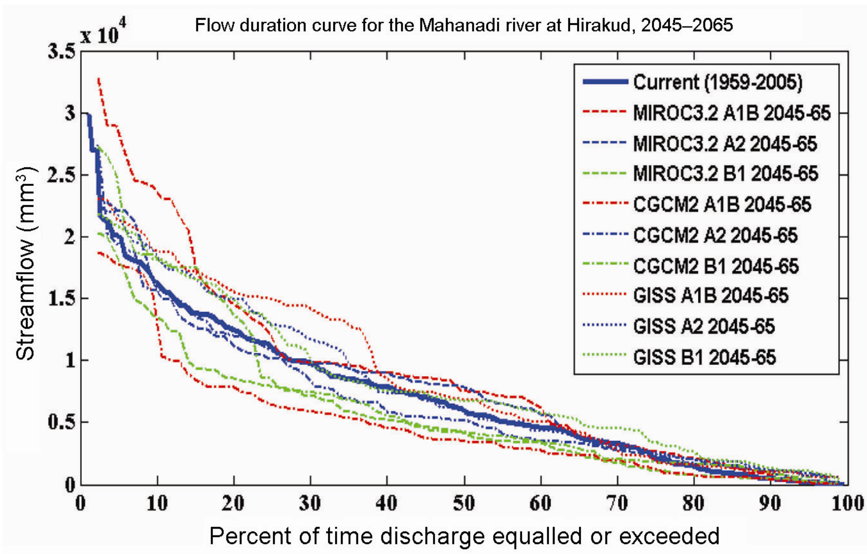

Figure 3. Streamflow prediction for the Mahanadi river[5].

by short-duration high-intensity rainfall, which will increase with time. So, the two main conclusions we could draw are: (i) seasonal streamflow in the Mahanadi is likely to decrease (Figure 3) and (ii) floods are likely to increase (Figure 4).

How frustrating is it to gain access to data on water resources?

In the past data sharing was not as good as it should have been, owing to the water disputes between states and each state was trying to hold back their data. Consequently, it was difficult for us to get complete information. But in the recent past it has improved, mainly due to Water Resources Information System (WRIS), an authentic database from the Central Government. The Narmada Control Authority (NCA) shared some data as the studies we did were useful to them. If the work we do is sponsored by a Government department dealing directly with planning and operation of structures in a riverbasin, we get easy access to data. But when our models are still at the research level, obtaining data is extremely difficult. In fact, many of my students get frustrated in trying to just obtain data to test their models, and we often rely on the data from other countries to test our scientific hypothesis.

It is quite disappointing if we are unable to test our models on our own river systems and instead have to apply them on systems outside India. For instance, to test our most recent work, we could not access data of Indian rivers and hence were compelled to test it on Columbia and Colorado rivers. These are the frustrations we face and most Indian scientists demand for an open and easy access to data. I am hopeful that with WRIS and similar initiatives things will improve.

Can your simulations be extended to other major rivers of India?

The Mahanadi and all peninsular rivers are rainfed, whereas the Himalayan rivers are both rain-fed and snow-fed. If temperatures are likely to increase due to climate change, contributions from snow melting might be higher in the Himalayan rivers. We will clearly have to modify the existing models to account for this. It is not only desirable, but urgently needed to develop climate change studies on all river basins in India through scientifically rigorous methodologies. I must acknowledge that IIT Delhi carried out a broad, first cut study on the Indian river basins some time ago, but that was for the purpose of communication to the international community.

The Ministry of Water Resources, Government of India (GoI) wanted similar projections for the major river basins of India. Since this is a large-scale project, a single group or institution cannot carry out all the work. So, a consortium of IITs and IISc was formed and we were willing to share all our work and methodologies with other institutes. Unfortunately this initiative was shelved midway. We are always keen to support any initiative of this kind.

What is detection and attribution?

Climate change leaves behind its signature in hydrology akin to a criminal leaving behind his fingerprints in a crime scene. We have to first detect this 'fingerprint' and then attribute it to the suspect – climate change. This in essence is the detection and attribution theory. Fingerprints could broadly be a change in the trend of a certain hydrological parameter observed in the last 60–70 years of data. Suppose we detect a sudden change, say decrease in the streamflow of the Mahanadi, this needs to be attributed to the right cause. It could be because of deforestation or urbanization or due a large demographic change, or it could indeed be due to climate change. It is more of an elimination process where we attribute a change to each of the possible causes and see if the observed change can be simulated using the models. If none of the natural causes explains the observed hydrologic change, but the anthropogenic climate change explains it better, then we attribute this to climate change. In the case of the Mahanadi river, we could not unequivocally attribute the hydrologic change to climate change as there are a large number of other forcings that contribute to it in the basin. Our current research focus is on developing methodologies to segregate the effect of these different forcings (such as change in land use, for example) on the hydrology. This is an extremely challenging problem and has not still been attempted satisfactorily. With a propitious combination of creative thinking, innovation, rigorous programming and time we should be able to crack this problem.

Why does it flood in the cities? Your work on urban flooding…

Consider two situations: a pristine forested area and an urban area. When there is rainfall, most of the water in the forest is infiltrated and the run-off increases slowly with time, whereas in an urban area there is little or no room for infiltration and most of the water goes as run-off immediately. In Figure 5, notice that the peak is reached sooner and the total run-off, the area under the curve, is visibly higher in an urbanized region than non-urban area because most of the rain is immediately being converted to run-off.

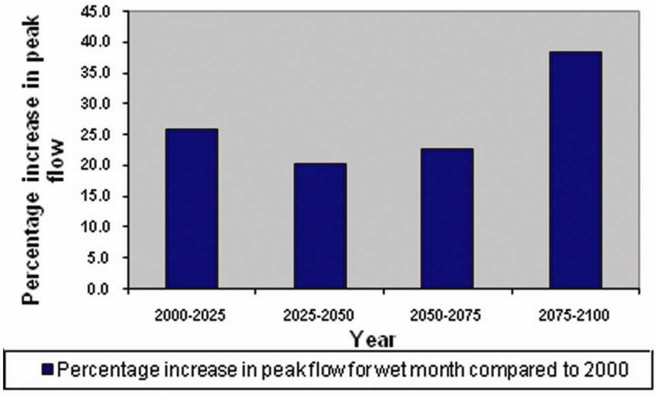

Figure 4. Percentage variation in peak discharge projected for the Mahanadi river[6].

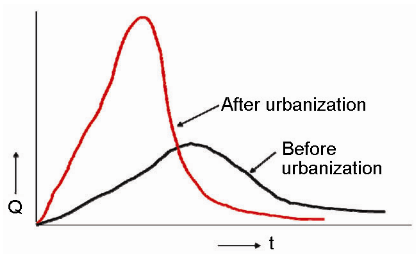

Figure 5. Hydrograph depicting run-off with time. *Q* is run-off rate and *t* is time.

Drainage systems in cities have been designed for a certain level of flooding, but cities have outgrown this and have encroached natural water pathways. So the systems built 20 years ago are no longer adequate for today's situation; consequently rainwater gets congested leading to floods. In addition, the storm-water drainage is blocked by solid waste leading to excess flooding. This is only a part of the story. Flooding is primarily caused by high-intensity rainfall in a short duration. Due to climate change, these events would likely increase with time. So on the one hand, urban land-use pattern is messed up and on the other, something is also happening in the atmosphere which is likely causing an increase in the intensity of rainfall. So together they aggravate the problem (Figure 6).

Coastal cities like Mumbai have a different story to tell as the tidal fluctuations also play a role in the flooding situation. Cities in which a river flows like Baroda and Allahabad, also have different problems of their own. Our current work is relevant to places such as Bengaluru and Hyderabad, but can be readily extended to other cities.

Can you predict which areas experience greater flooding and suggest measures to prevent them?

Naturally, low-lying areas are greatly affected because drainage by gravity is impossible. We have now taken up a comprehensive study sponsored by the Information Technology Research Academy, Ministry of Communications and Information Technology in association with the Karnataka State Natural Disaster Monitoring Centre and Bruhat Bengaluru Municipal Corporation (BBMP). BBMP has provided us with a study area and the other agencies are supplying us with data and information. I must acknowledge IMD, Bengaluru, which has provided us with the 15-min rainfall data in the city, needed for the study. M/S Stup Consultants, who are involved in remodelling the storm-water drainage as consultants to BBMP, have been forthcoming with data on infrastructure and digital elevation models. Since only part of the study area is developed, this gives us an opportunity to experiment with different solution methodologies. We are trying to come up with an end-to-end management solution for urban flooding. If we have rainfall forecast at a lead time of a few hours, we should be able to predict the flooding patterns in urban regions and hence suggest prior measures. There are models to do so, but we need a lot of help from several government organizations. It is quite ambitious, but we are hopeful it will be possible.

I have taken up this quite seriously because as responsible scientists, instead of blaming our chaotic infrastructure or messed-up water systems, we must ask what best we can do to improve the situation. Urbanization is a reality and we cannot demolish all buildings to go back to living like in the 19th century; it is simply unrealistic! I hope we succeed in providing implementable solutions to the urban flooding problem.

What are your predictions of water quality in the Tunga Bhadra river?

We have developed a model that projects the effects of climate change on the dissolved oxygen (DO) levels in the Tunga Bhadra. There are already too many stresses due to the influx of pollutants from the industries all along Tunga Bhadra, which are harming the water quality. What we project is a further decrease in the DO level if we add another stress – climate change. For instance, if the temperature rises by 1°C and streamflow reduces by 10%, what would be the oxygen content? Such simulations predict an alarming rate of decrease in oxygen (Figure 7), for the existing datum status of effluent discharges.

Our models answer 'what if' kind of scenarios. Given the current conditions, we can also predict how water quality can be improved if a particular level of treatment is provided to the effluents from an industry. Policy makers can easily play around with our models on the computer and decide what rules and regulations must be implemented to prevent further harm in the next few decades.

Have you communicated your suggestions to the policy makers?

Communicating to policy makers is quite difficult and there are several levels of communication possible. One level is where we suggest what methodologies should be followed in managing water resources, like through the consortium I mentioned earlier in association with the Ministry of Water Resources, GoI. Another level is when they approach us for help, as in the case of the Narmada authorities.

As a ready product, we did develop a good package for water allocation, which unfortunately was not taken forward. It still saddens me that after putting in

Figure 6. Bengaluru floods[7,8].

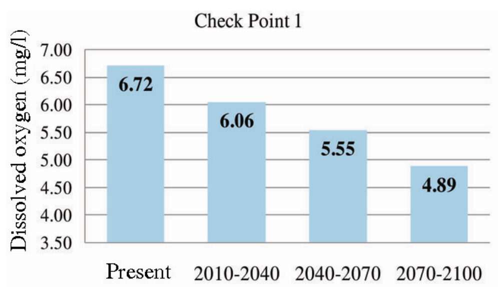

Figure 7. Declining oxygen levels of the Tunga Bhadra[9].

enormous effort, the project never saw any implementation at the field level.

Imagine a canal command area with a hamlet of about 100–200 farmers. The question is: how can water be allocated to all these farmers? About 10 years ago, our computer science colleagues at IISc had just then come up with low-cost, hand-held computers called simputers (Figure 8). Recall that it was a time when tablets were not still developed. On these platforms of simputers, we developed water allocation models integrated with complete database. Every farmer would be given a smart card with all his details such as name, number of people in the family, number of cattle, farm size, crops, crop condition, marketing methods, fertilizers, etc. Based on the farmers' needs we had a model that would allot the required amount of water to each farmer, during each ten-day period in a season. For instance, if a particular farmer's soil moisture is less, or a certain crop is in critical condition, then that farmer will be assigned more water. Keeping the conditions of all other farmers in view, in a multi-objective optimization framework, we did everything at the research level and demonstrated with a case study. But it failed to reach the policy makers – perhaps the blame should be ours, but we had done our part of the job.

Apart from this, I have been consulted by the Government of Karnataka during the Krishna river dispute; we have also helped the Narmada authorities in their reservoir operation and there are a few other interactions I have had with the policy makers. But overall, being academicians, we are rather shy to approach the policy makers ourselves – we would rather make our work talk.

In your Von Humboldt medal lecture, you say you are thankful to many international collaborators. How important were these collaborations for your work?

I am completely an India-bred person and have done all my education in India. Naturally, during my initial days we did not have many international collaborations and research work was purely driven by academic passion. But, in recent years we have had collaborations and I am particularly thankful to late Toshiharu Kyojiri from Kyoto University, Japan, who provided an international platform for our work. This gave an impetus to our other collaborations and, specifically, my interactions with Upmanu Lall, IRI Columbia University, benefited me a lot. We now have a massive project with Imperial College London, and are dealing with change in water storages in the upper Ganga Basin. This is a huge consortium where scientists from IISc and Imperial College are helping each other in developing rigorous climate models.

But these collaborations are quite recent. I am mostly thankful to my bright doctoral students because of whom I have been able to do good work. In fact, my doctoral student Subimal Ghosh, who is currently a faculty in IIT Bombay, was perhaps the first to build climate change models in India. Also, IISc played a key role in building my academic niche. Most of the research projects I have led also have my colleagues as co-investigators and I give due credit to all of them in shaping up the work.

How important are awards and recognitions?

Initially awards were important since we are competing at the international level; any sort of recognition helps. I was given the CBIP Young Engineer award as soon as I joined IISc and I was still an assistant professor. So, recognition at the national level at a young age obviously gave me an enormous boost. The Satish Dhawan award was also important. But in the recent times passion for good qualiy work overrides a desire for external recognition through awards. But I would be dishonest if I say that awards and recognition are not important to me at all. Awards such as the Von Humboldt medal (Figure 9) boost my morale because I know someone out there recognizes and appreciates the quality work we are doing. But eventually, satisfaction comes from within. I often tell my students that it is not the number of publications or the citations that matter, but it is those few good papers which are innovative, original and creative that bring maximum satisfaction. Ultimately, recognition and satisfaction must come from within and even without awards one can – and should – feel satisfied!

What makes you happier? The scientist sitting in front of the computer and mindfully exacting models, or are you more happy teaching, because your lectures on YouTube have several views and likes?

I would say it is a combination of both. Personally, I enjoy teaching and it is something that brings me immediate happiness. It is like sugar or chocolate that gives an instantaneous boost. I spend hours thinking on how to convey a difficult topic and after the class I would

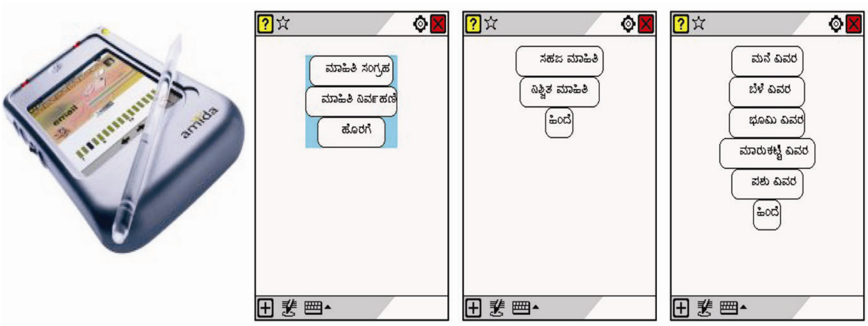

Figure 8. Simputer and a typical data collection screen.

Figure 9. Pradeep Mujumdar delivering the Von Humboldt medal lecture at the European Geosciences Union Assembly, Vienna 2014.

know if I have done a good job and it is very satisfying.

But doing high quality research is a long process; one needs perseverance, commitment and patience. So, in the long run, happiness derived out of research is longlasting when compared to that of teaching. Specifically, I love sitting with my students for discussions after dusk, when the hustle-bustle of the day has settled and the institute wears a quiet and silent academic look. It is then we discuss new ideas and methodologies to fine-tune our theories and much more. This part of the work gives me immense pleasure and satisfaction.

Message to youngsters who wish to pursue hydrology...

I often tell my students that hydrology is an important and fertile field to work in. Since the issues we deal with are related to water, these studies are crucial for sustaining the future of humanity. The current trends indicate rise in floods and droughts and the additional stress due to climate change. So, this is a great opportunity for the youngsters to contribute meaningfully and creatively. High level of scientific input in this field is vital to bring about good policy interventions. Hydrology borders on basic and applied sciences as it involves understanding hydrological processes from an earth science perspective and at the same time, hydrologists are required to provide solutions to the existing problems from an engineering perspective. Students must enter into higher studies to pursue this area because during an undergraduate degree, exposure to hydrology is limited. It is only during an M Tech and Ph D that students learn hydrology in some detail. It is the right time for youngsters to explore this area and pursue it with all passion and I assure you, it will be highly rewarding.

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G. V. Punyakoti, S. Ramaseshan Fellow.
e-mail: punyakoti.gv@gmail.com